Agenda
Help
Summary

Next Steps Towards a Commercializable Coated Conductor

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Superconductivity Technology Center
Los Alamos National Laboratory

FY2005 Funding: $1.5 M, 5 FTE

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Outline

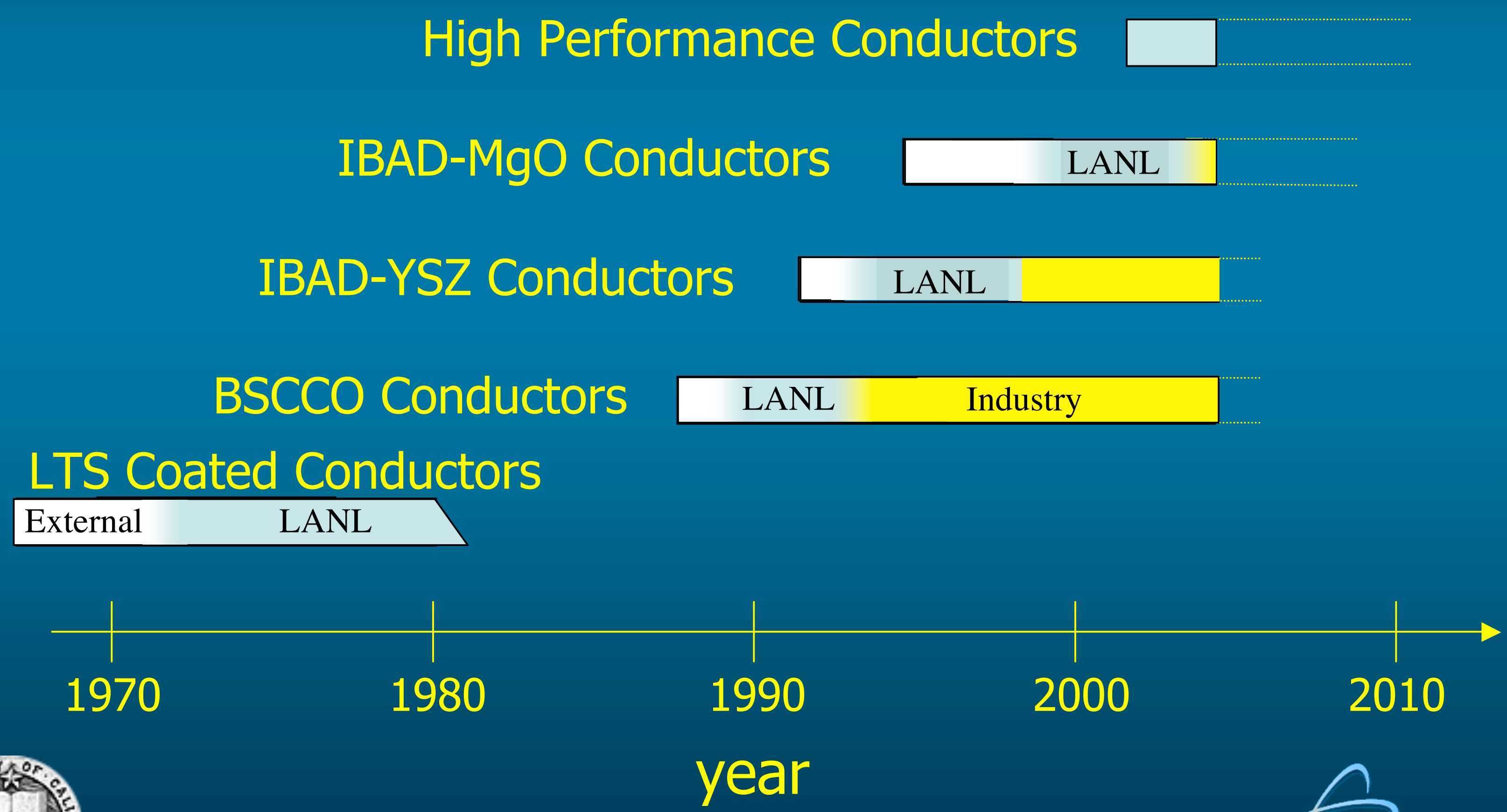
- Introduction (VM)
- Template (VM)
  - IBAD architecture
  - IBAD process achievements
- Superconducting results (BJG)
  - uniformity
  - high current results
- Conductor design (SA)
  - ac losses
  - stabilization
- Summary slides (SA)

Los Alamos CC Achievements - FY05

- **IBAD template**
  - Reduced the time for high quality IBAD to less than 2 seconds
  - Simplified the IBAD stack by eliminating one layer
  - Started research into a new tape preparation process with a sol-gel layer
- **Superconducting results**
  - 350 A on 1 meter
  - 530 A/cm-width on moving short samples
- **Conductor design**
  - ac losses reduced by two orders of magnitude
  - Introduced a manufacturable process for reduced losses

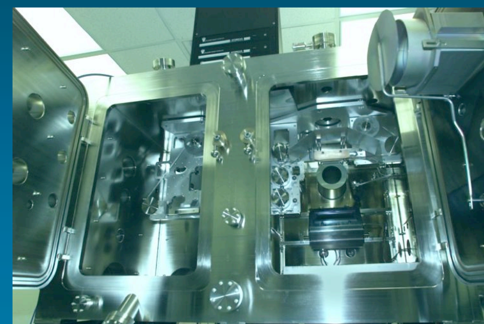
Introduction to LANL R&D

- Los Alamos plays an integral part in HTS wire development
- LANL bridges research and product development

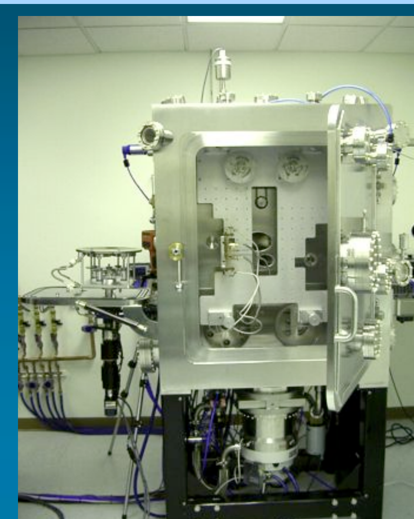


Reel-to-reel fabrication and characterization capabilities set up for research at LANL

Electropolishing



IBAD template

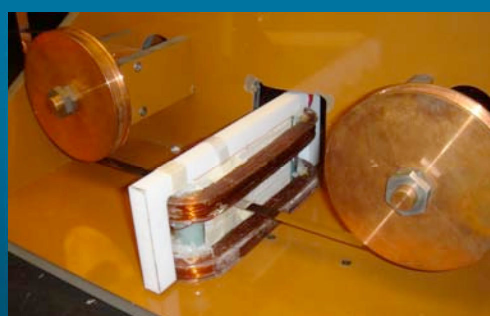


PLD buffer/HTS + Ag

- Systems are adaptable to the needs of our industrial partners

Conductor fabrication

Positional I_c

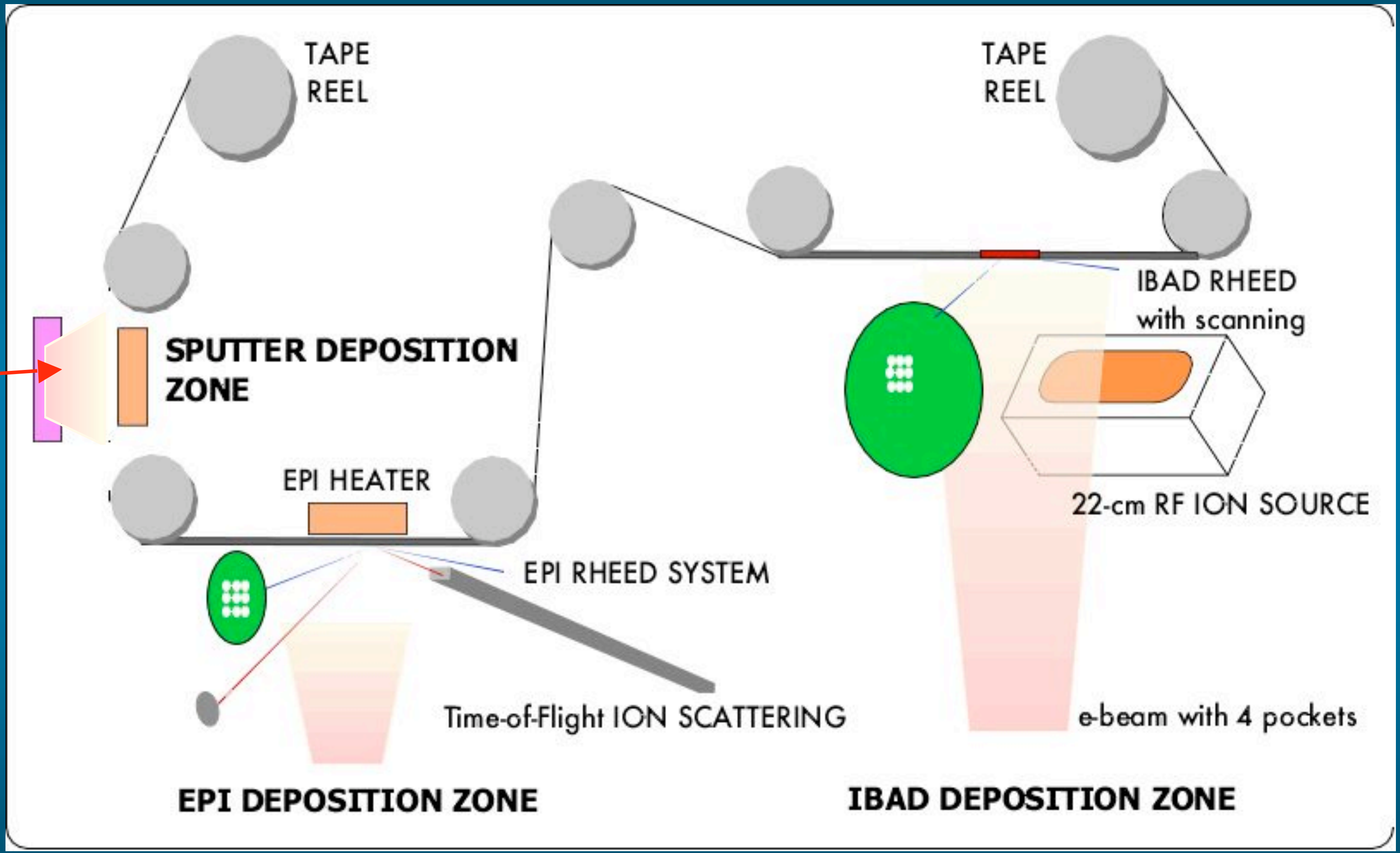


Positional ac losses

Schematic of LANL IBAD Reel-to-Reel System

NEW

Sputtering used for: Ta_2O_5, TiN

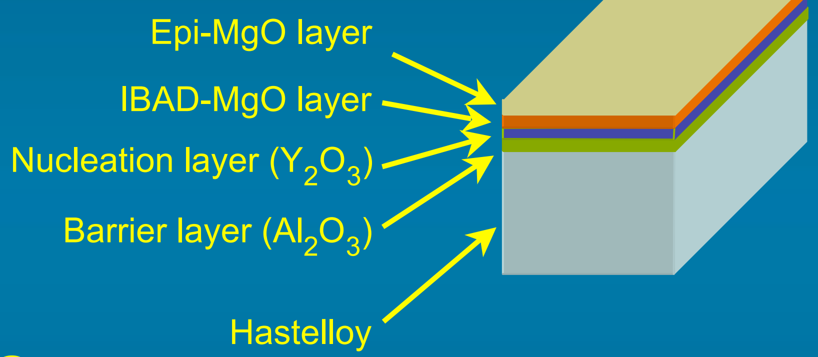


- Flexible for R&D of various deposition sequences

Simplified the IBAD-MgO Architecture

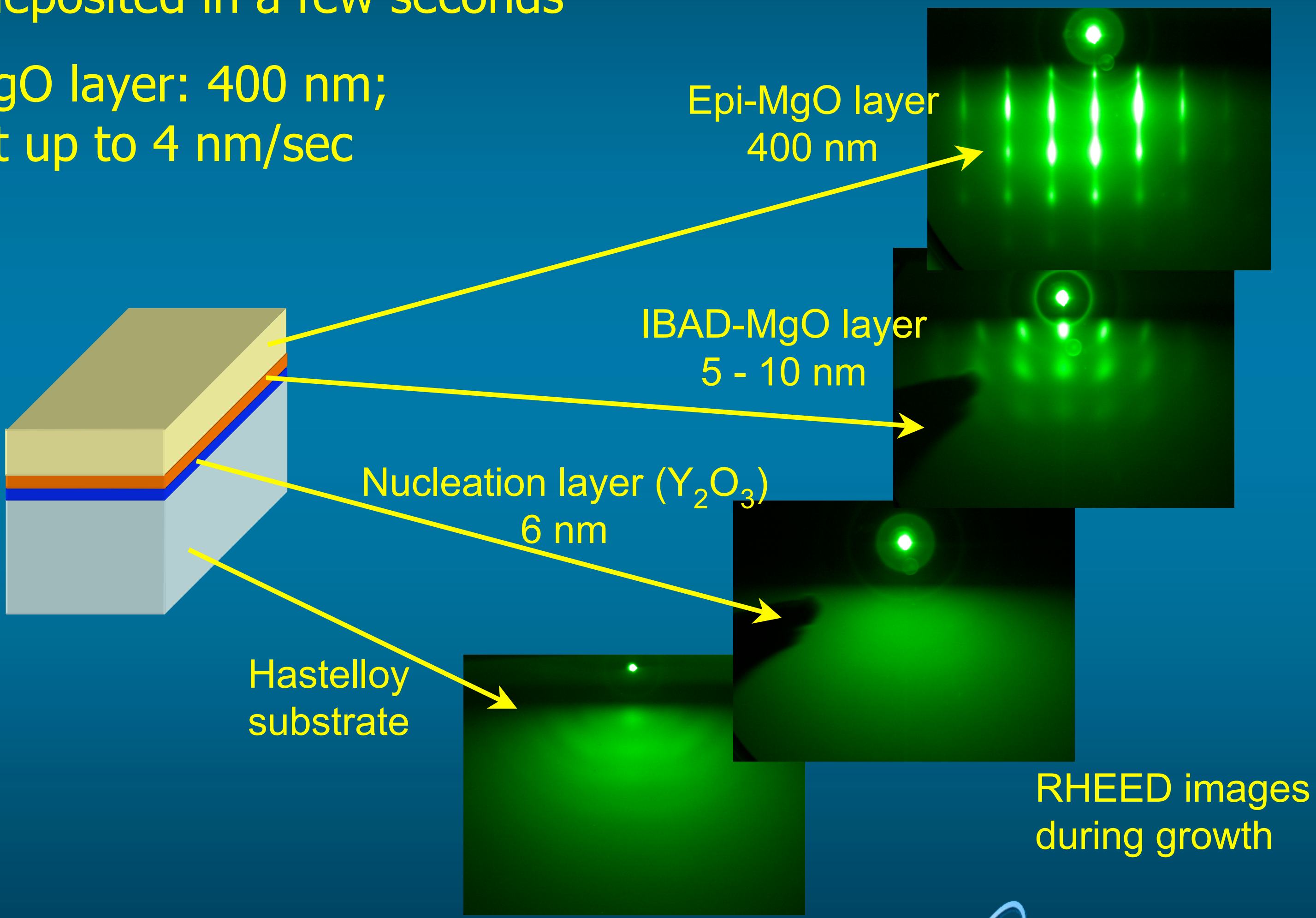
- Wanted to make the IBAD layer stack more robust to withstand a higher thermal budget
- Can increase thickness for:
  - Al_2O_3 layer or
  - MgO layer
- Decided to make a thicker MgO layer and remove the Al_2O_3 layer
- Simpler architecture, bonus is better texture and less Al interdiffusion

Original layer stack:



Implemented a robust and simple IBAD architecture

- Y_2O_3 layer deposited in a few seconds
- Thick epi-MgO layer: 400 nm; deposited at up to 4 nm/sec



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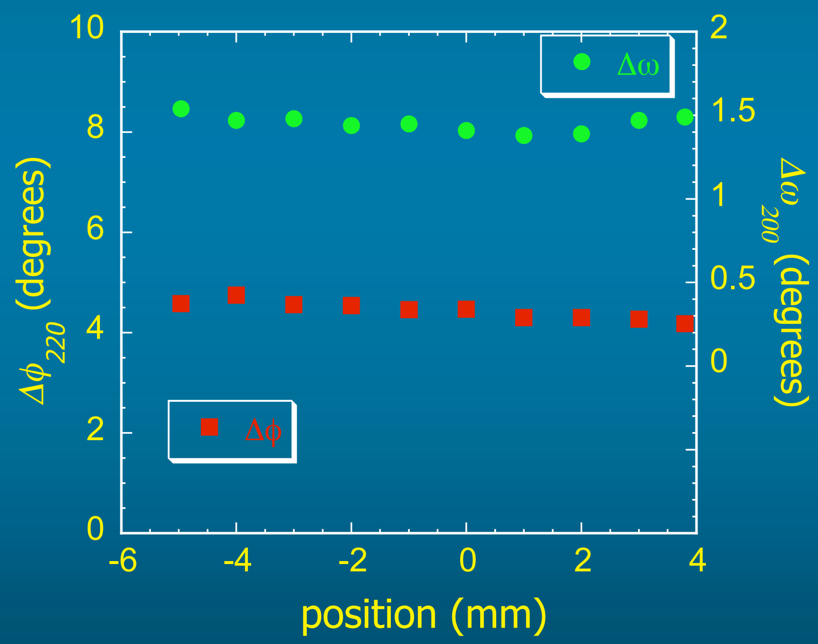
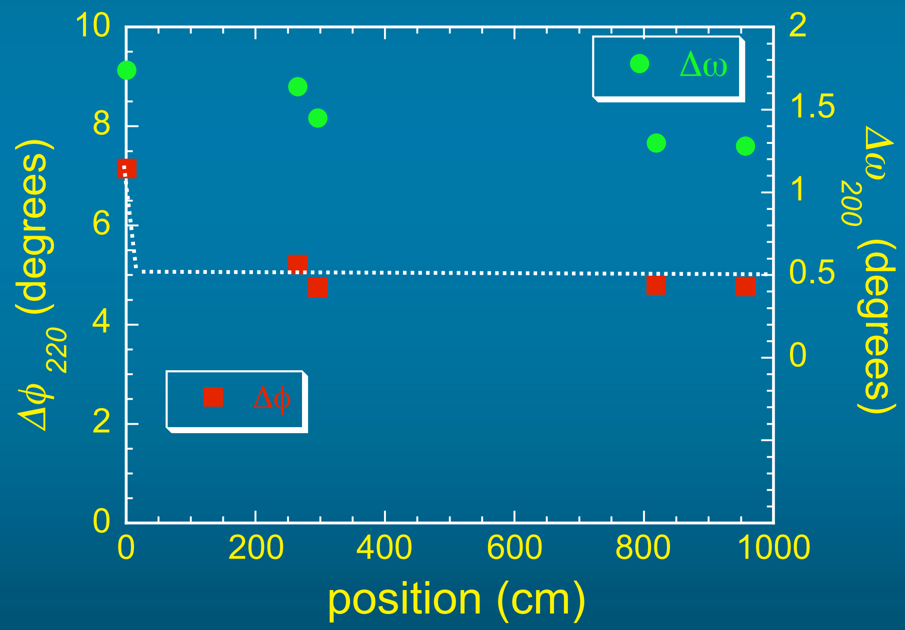
IBAD-MgO tape uniformity is good with improved texture

- 10 m lengths fabricated with in-plane texture of 4 - 6°

Texture across the width of tape

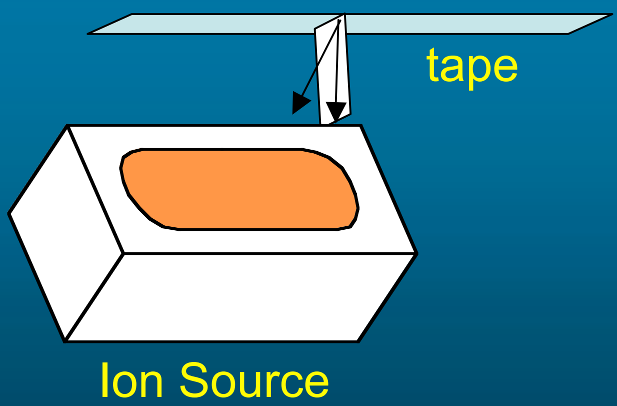


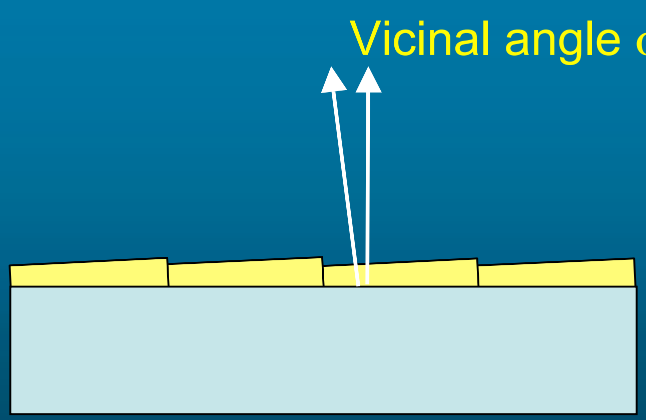
Texture along 10 m of tape



IBAD-MgO films typically exhibit some tilt

- Tilting of the MgO lattice is known to occur during IBAD in the plane of the ion direction (i.e. plane perpendicular to tape direction)
- We typically observe a tilt in our films of 2 - 4°
- Tilting of the IBAD lattice determines the vicinal angle
- Tilt is then transferred to the subsequent layers
- Understanding of tilt is poor, but it is known that IBAD ratio and thickness affect tilt





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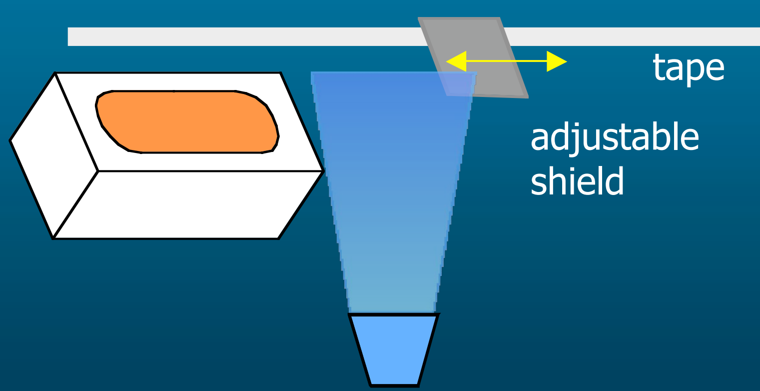
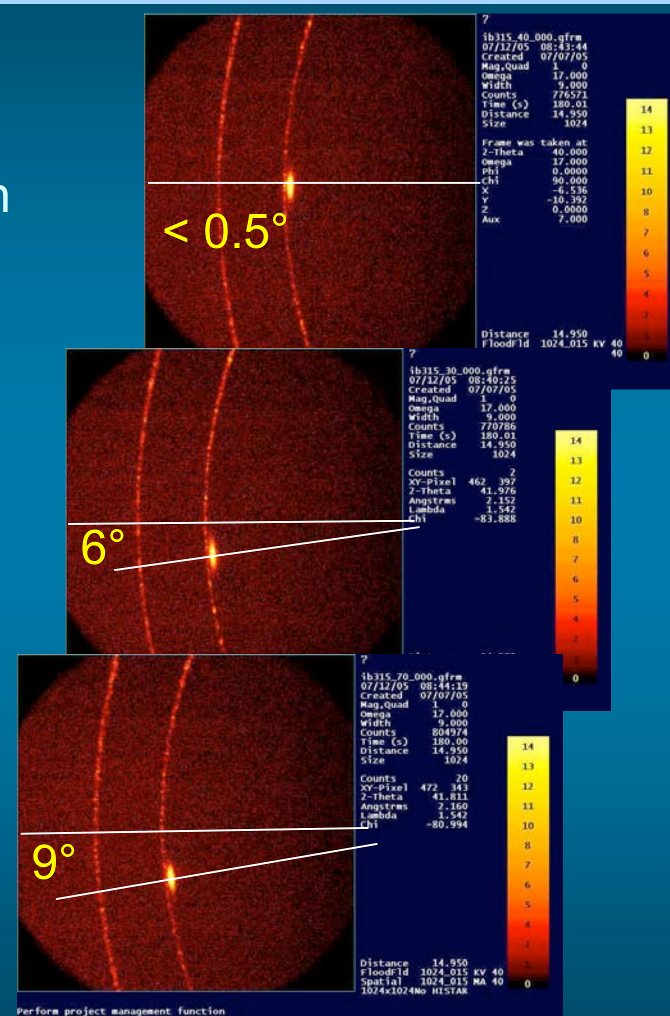
Engineering of the tilt in the IBAD film is possible

- Discovered: can modify the tilt by pretreatment of the nucleation layer
  - by changing the thickness of the nucleation layer & ion beam treatment
- Have implemented this with moving tape by adding an adjustable shield to screen the MgO deposition at the start of IBAD
- So far have not observed a significant effect on J_c in tape direction

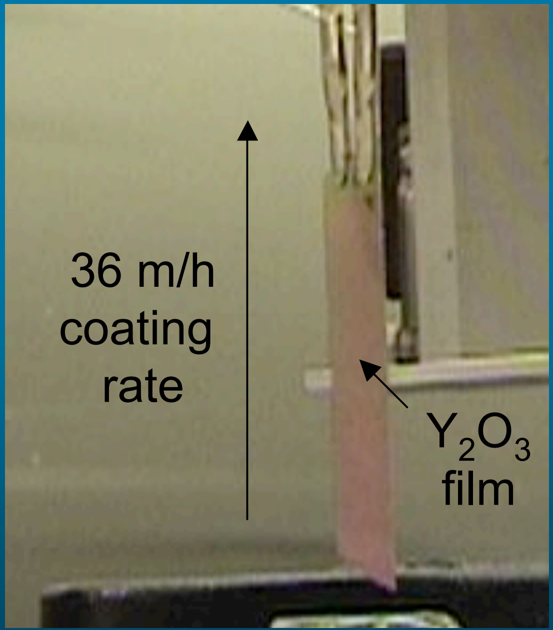




Started experiments with new sol-gel process for tape preparation

• Planarizing by sol-gel deposition on unpolished Hastelloy could avoid need for electropolishing

• Paul Clem (Sandia Natl Lab) used solution chemistry to deposit 150 nm films of amorphous Y_2O_3 on unpolished and polished Hastelloy substrates

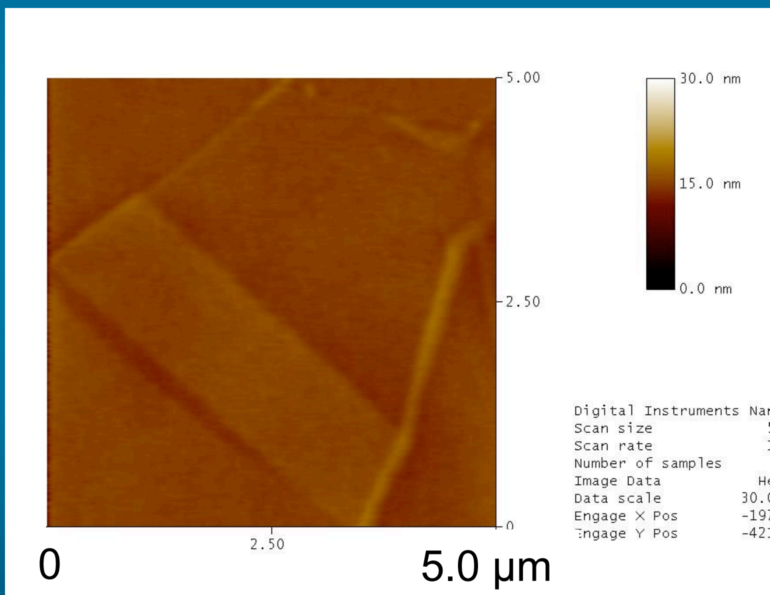


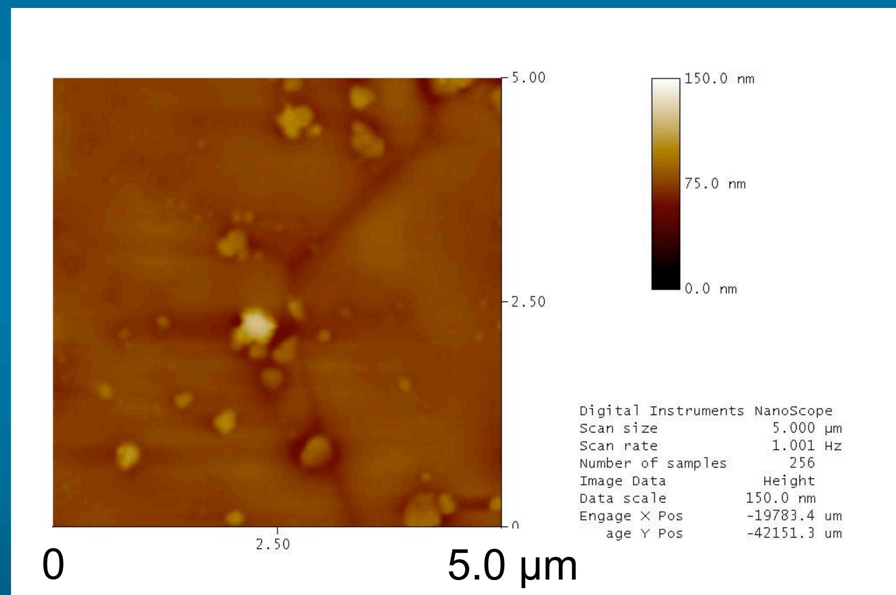
• Discovered that the Y_2O_3 sol-gel layer can be used as a nucleation layer for IBAD-MgO

Initial results seem promising for sol-gel

Y_2O_3 dip coating AFM RMS roughness measurements

polished Hastelloy	unpolished Hastelloy
bare: 1.0 nm	bare: 13.2 nm
Y_2O_3: 0.6 nm	Y_2O_3: 6.2 nm





IBAD-MgO: $\Delta\phi$=4.8° $\Delta\omega$=1.3°

YBCO J_c > 1.5 MA/cm^2

IBAD-MgO: $\Delta\phi$=6.7°

No YBCO result yet; needs more optimization

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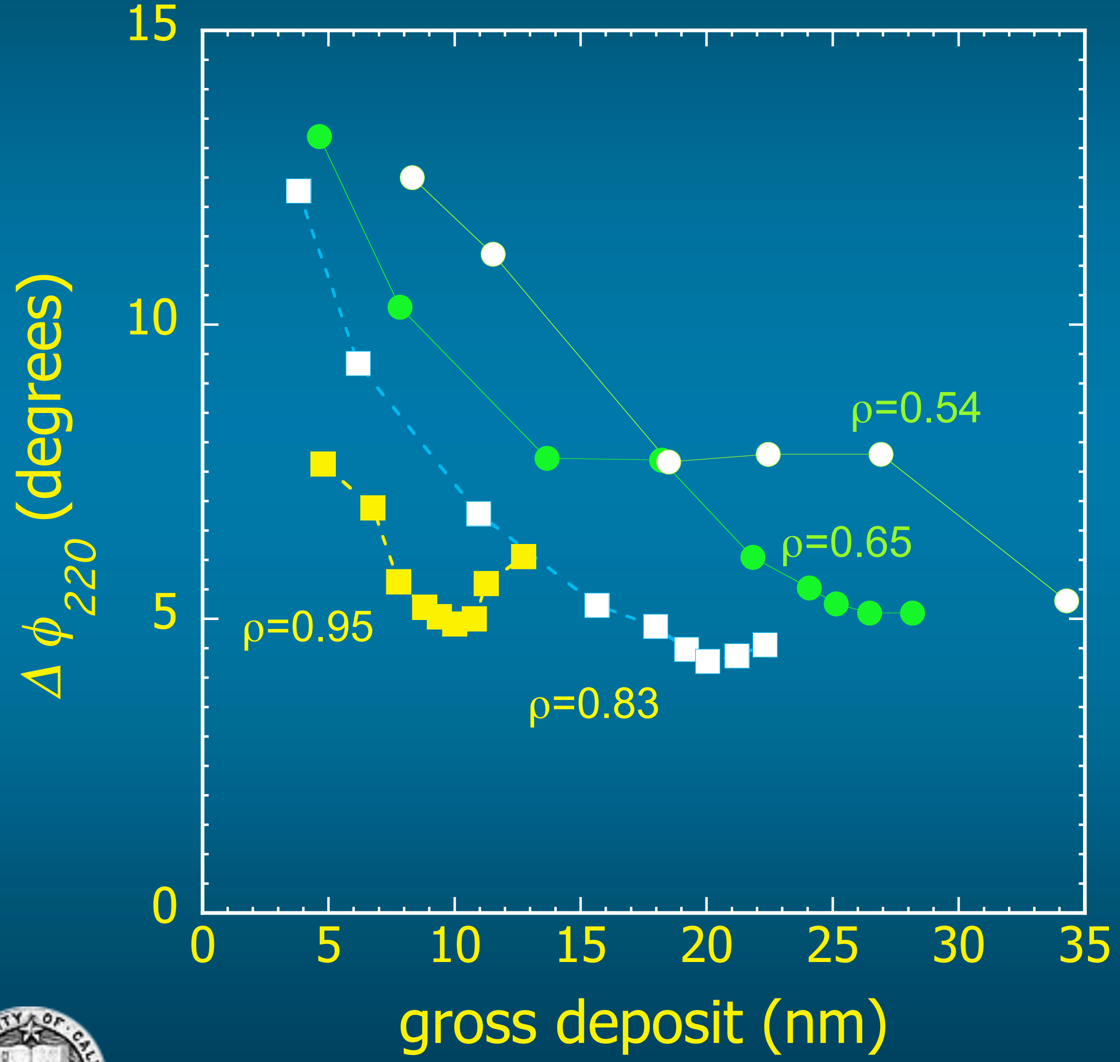
Advantages of a sol-gel tape finishing process

- Adaptable to any new metal substrate
  - Does not have to be tailored to a specific alloy
- Multiple coatings can smooth out the rougher starting substrates
- Coats both sides of tape to prevent oxidation of the back
- Coating provides a barrier layer to interdiffusion
- Ready as a nucleation layer for IBAD-MgO process

Sol-gel deposited Y_2O_3 looks very promising - still need more research

Last year we showed that IBAD-MgO texture depends on ratio *and* total deposit thickness



- Data shown for IBAD-MgO on metal tape with Y_2O_3 layer
- Best texture can be attained in a wide window for the ion-to-molecule ratio
- Other surfaces exhibit somewhat different behavior

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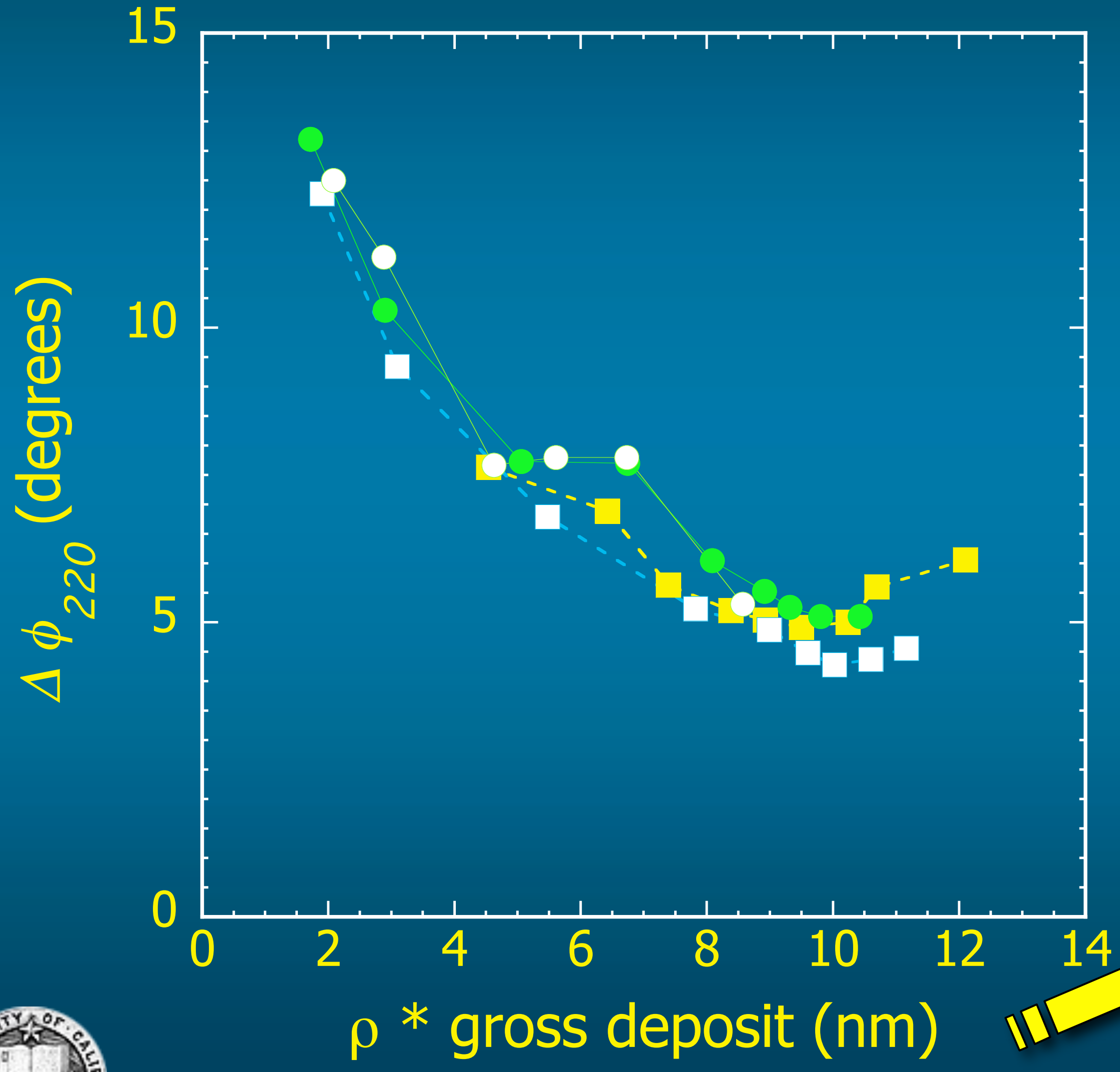
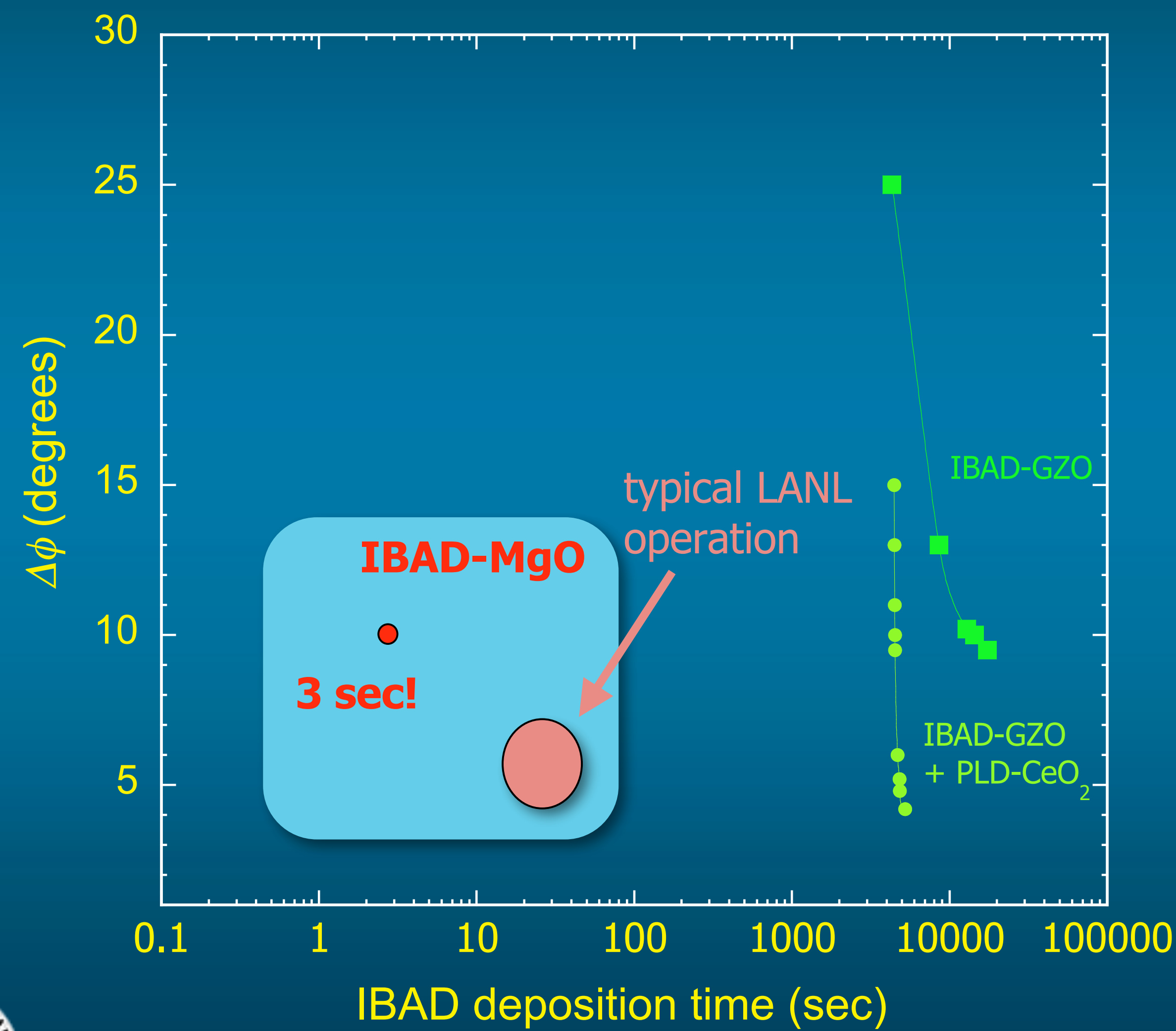
IBAD-MgO texture scales with total ion beam fluence



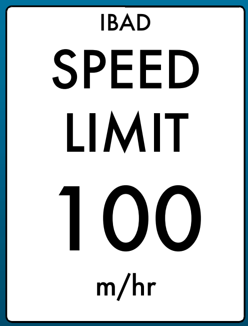
Speed of texture evolution is determined by ion beam fluence

Curves can be scaled with the amount of sputtered material

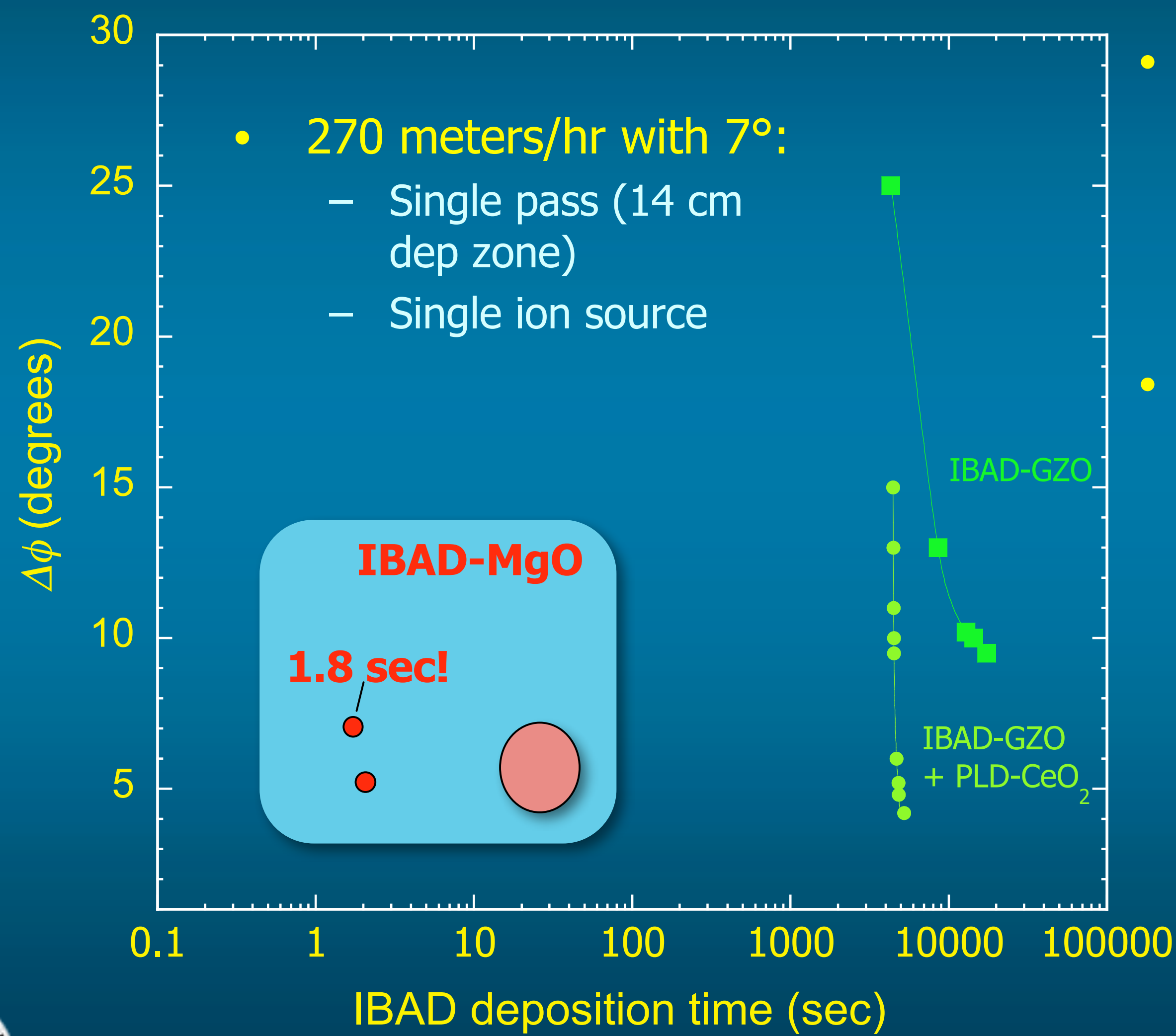
How fast can we make the IBAD-MgO?



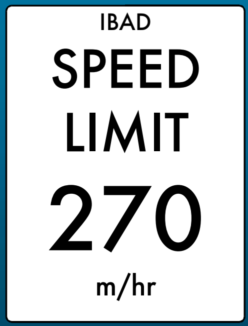
Last year demonstrated 100 m/hr in a single pass



Demonstrated IBAD-MgO texture in < 2 sec



- This year:
  - Increased dep zone to 14 cm
  - Optimized ion fluence
- Reduced the IBAD time to 1.8 sec for 7° in-plane texture



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Speed of template production

For realistic manufacturing costs need about 1 km/hr (cm-wide equiv.)

	Electro-polishing	~~Barrier layer (AlO)~~	Nucl. Layer (YO)	IBAD-MgO	Epi-MgO
Demonstrated speed (LANL) cm-km/hr	0.04	~~0.004~~	0.015	0.27	0.004
Lab capable speed cm-km/hr	0.2	~~0.02~~	0.2	1	0.015
Industrial scale up to 1 cm-km/hr	✔	~~?~~	✔	✔	?

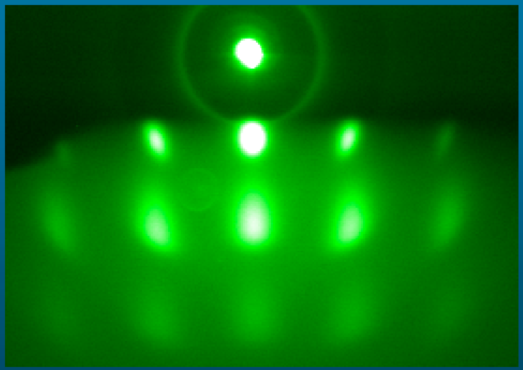
Throughput limited by epi buffer layer deposition

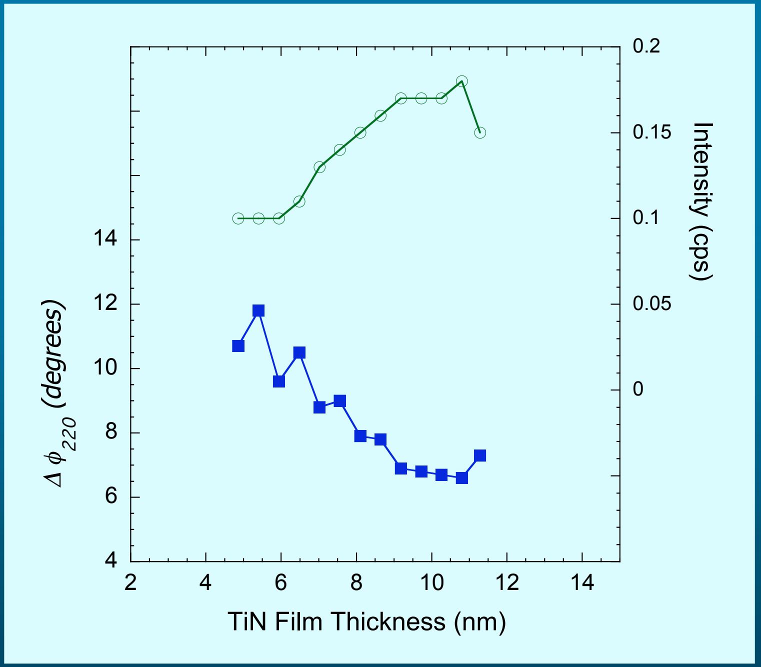
	Electro-polishing	Nucl. Layer (YO)	IBAD-MgO	Epi-MgO
Demonstrated speed (LANL) cm-km/hr	0.04	0.015	0.27	0.004
Lab capable speed cm-km/hr	0.2	0.2	1	0.015
Industrial scale up to 1 cm-km/hr	✔	✔	✔	?

New IBAD layers have similar texture evolution

- New IBAD materials: NiO, CrO, CoO, TiN
  - All seem to have similar type of fast texture evolution as MgO
- TiN is a conducting layer ($\rho \sim 25\ \mu\Omega$–cm)
- Opens up the possibility for a conducting IBAD layer stack
- Best result to date: 7° FWHM in-plane

Ion beam at 750 eV and 45°





Superconductor deposition on moving tapes

- All of the systems at the Research Park are designed for flexible operation
- Integrate new ideas into a reel-to-reel deposition environment
  - New materials
  - New architectures
  - New geometries/conductor designs
- This kind of research is easier in a non-manufacturing environment
- These demonstrations can then be integrated into our industrial partners' processes

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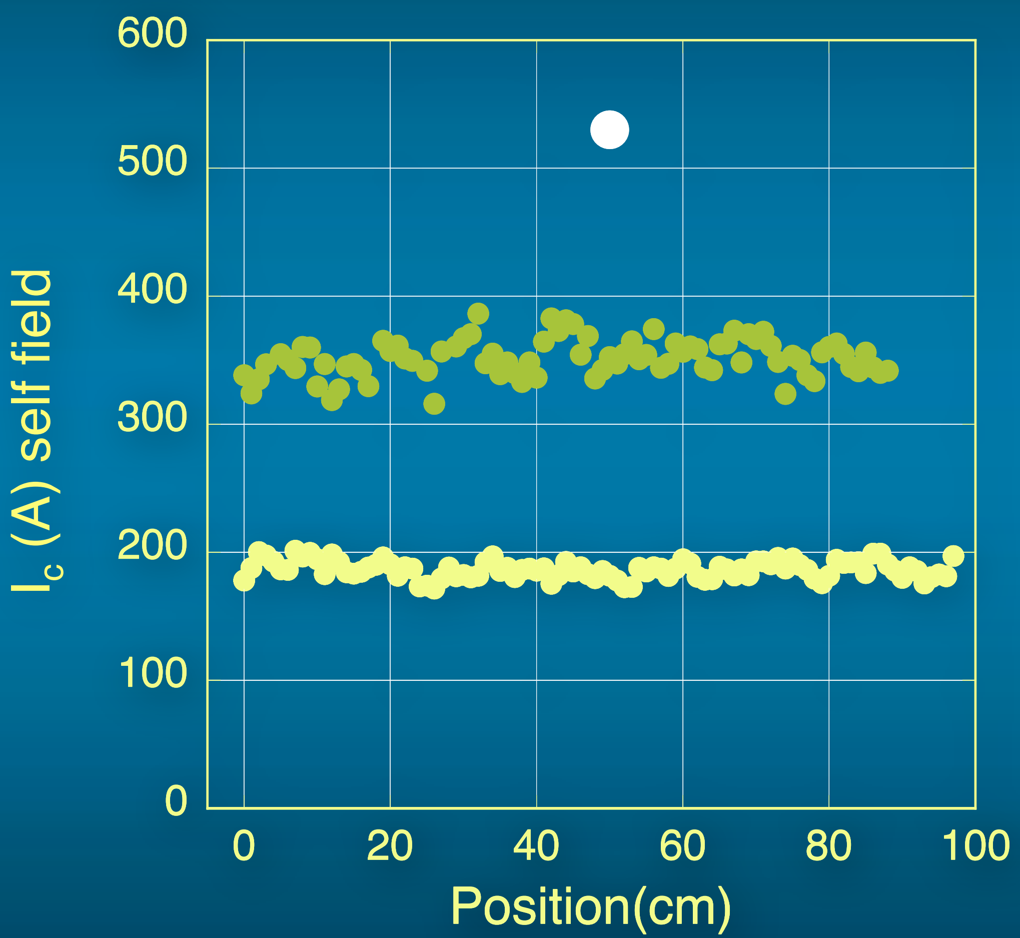
Progress since last year:

- Last year 172 A on 1 m (75 K)
- This year 350 A on 1.2 m
- This year 530 A/cm on 7 cm



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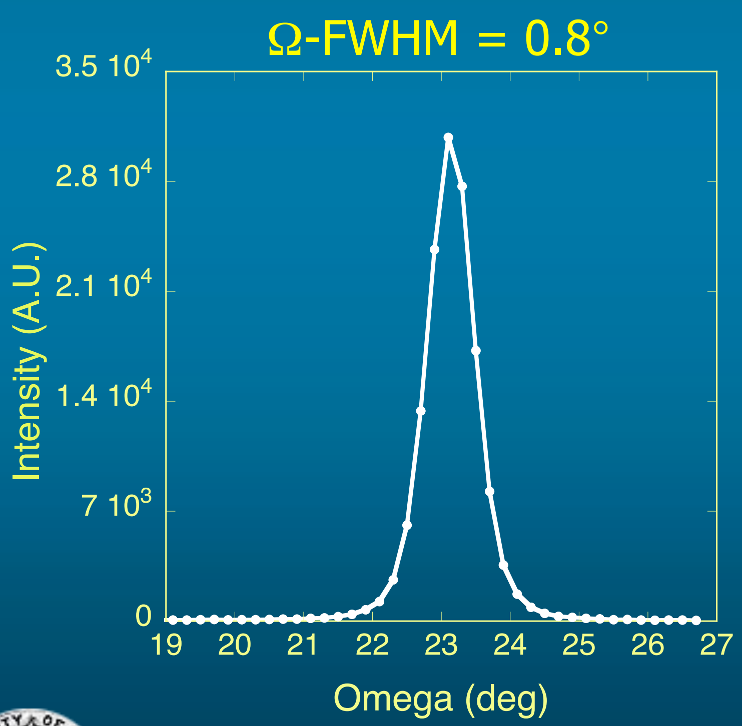
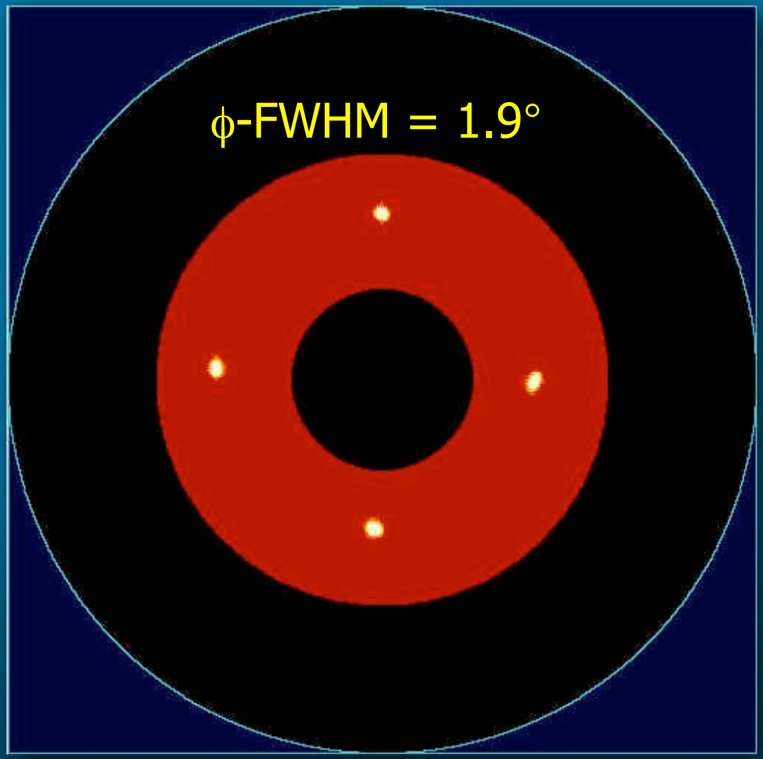
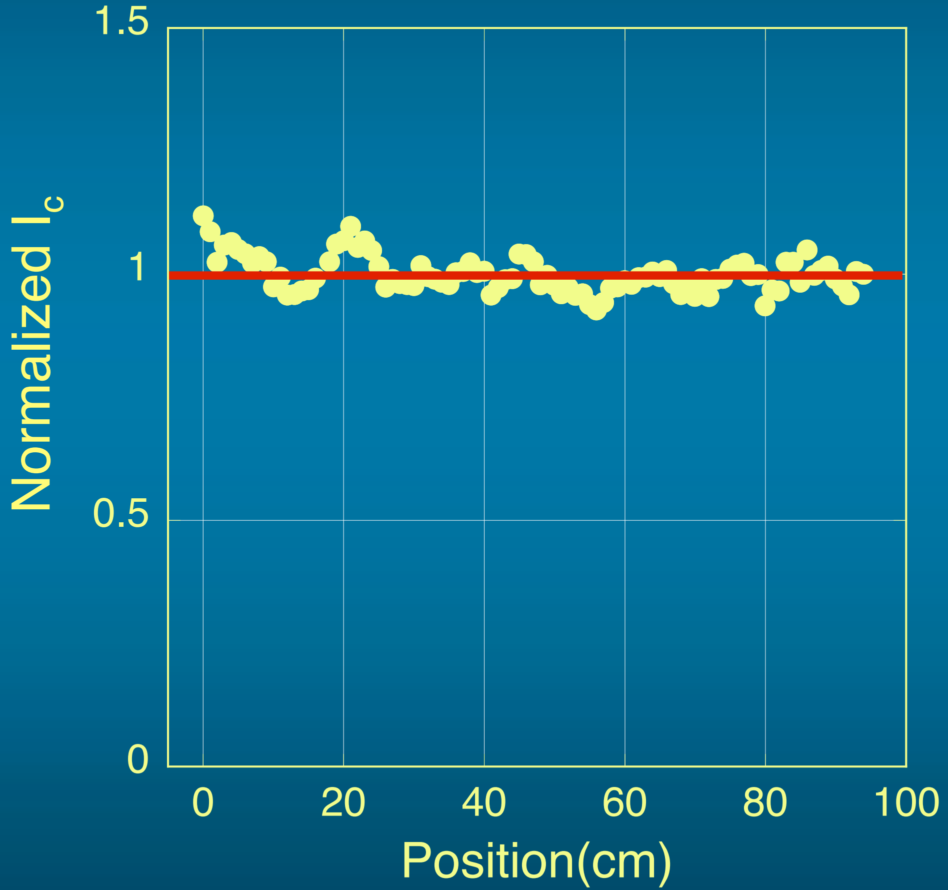
New IBAD architecture results in significant structural improvement

- In-plane and out-of-plane structural parameters are well below the limits of grain boundary effects
  - 2 μm YBCO film





Uniformity along the length



- Standard deviation ± 3.5%
- The most important factor is to eliminate current 'drop outs'

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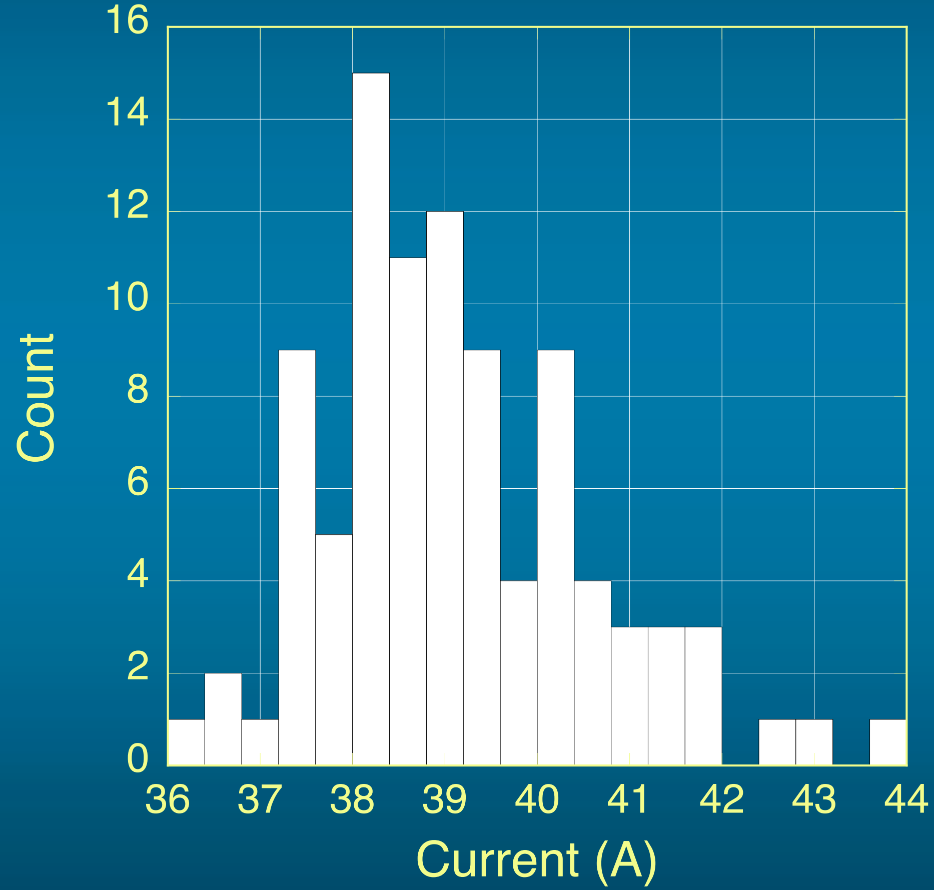
Uniformity along the length



- Standard deviation ± 3.5%
- The most important factor is to eliminate current 'drop outs'
- A histogram plot of these data indicate an asymmetric distribution with the tail extending to higher currents than the mean
  - Fewer and smaller 'drop outs'
    - 7% lower than mean

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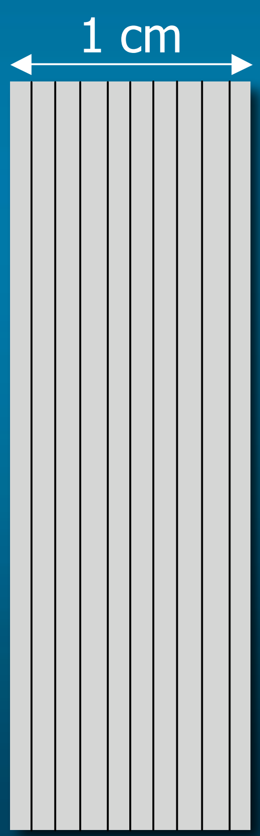
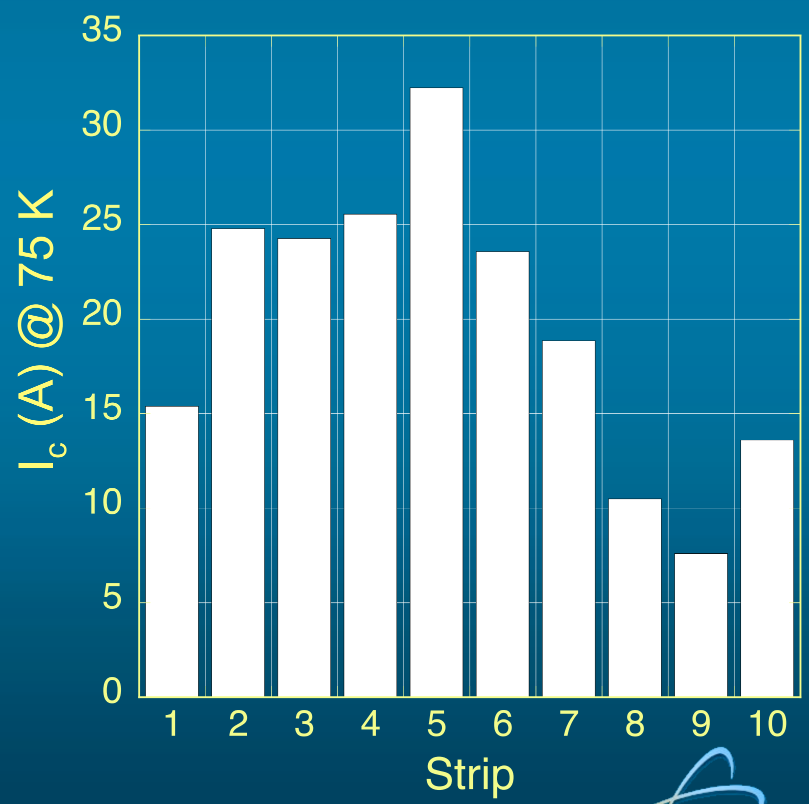
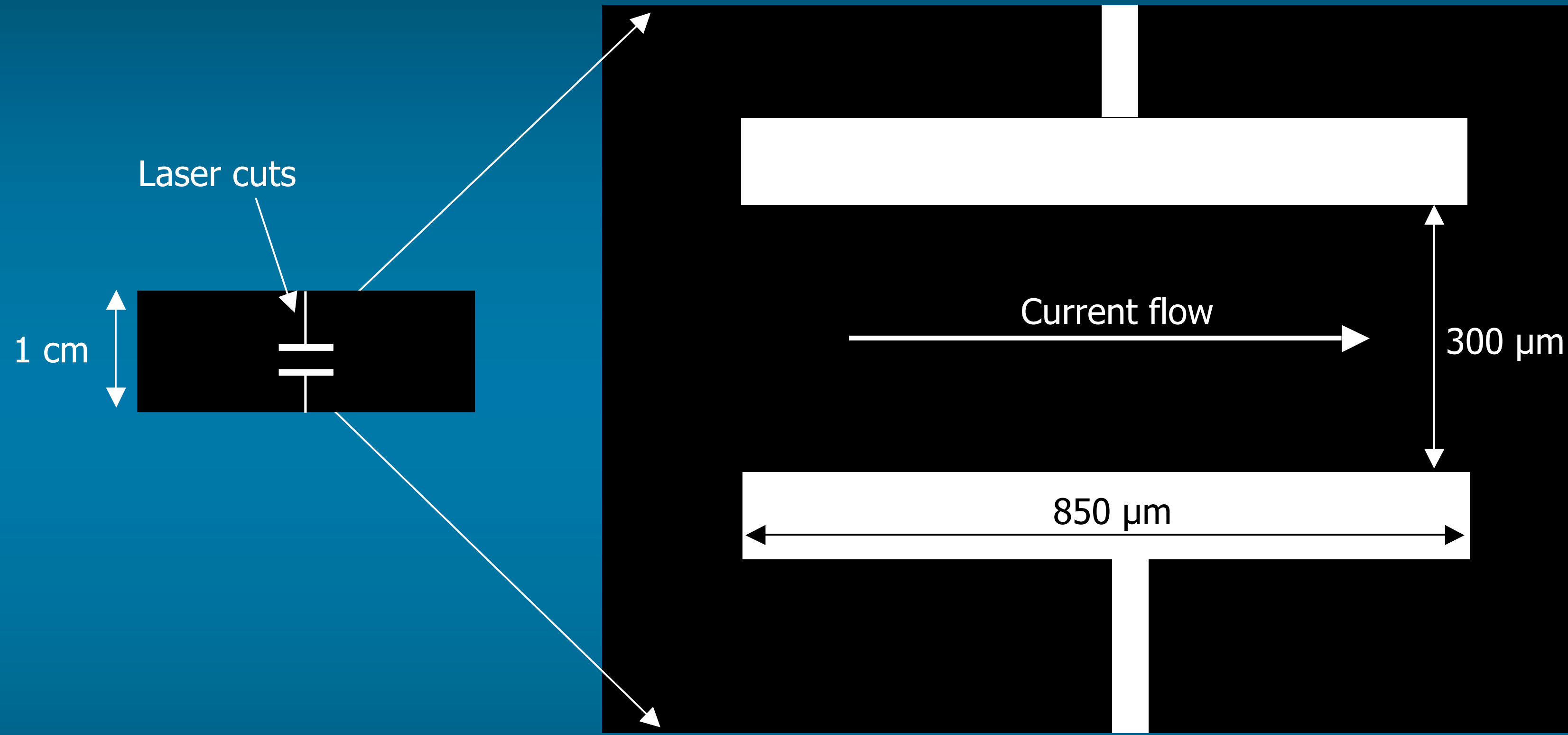
Width uniformity can be improved: The J_c for the entire width is lower than expected

- By scribing the tape into ten 1 mm wide strips and measuring I_c, non-uniformity across the tape can be seen
- The thermal environment at the edges is different during growth



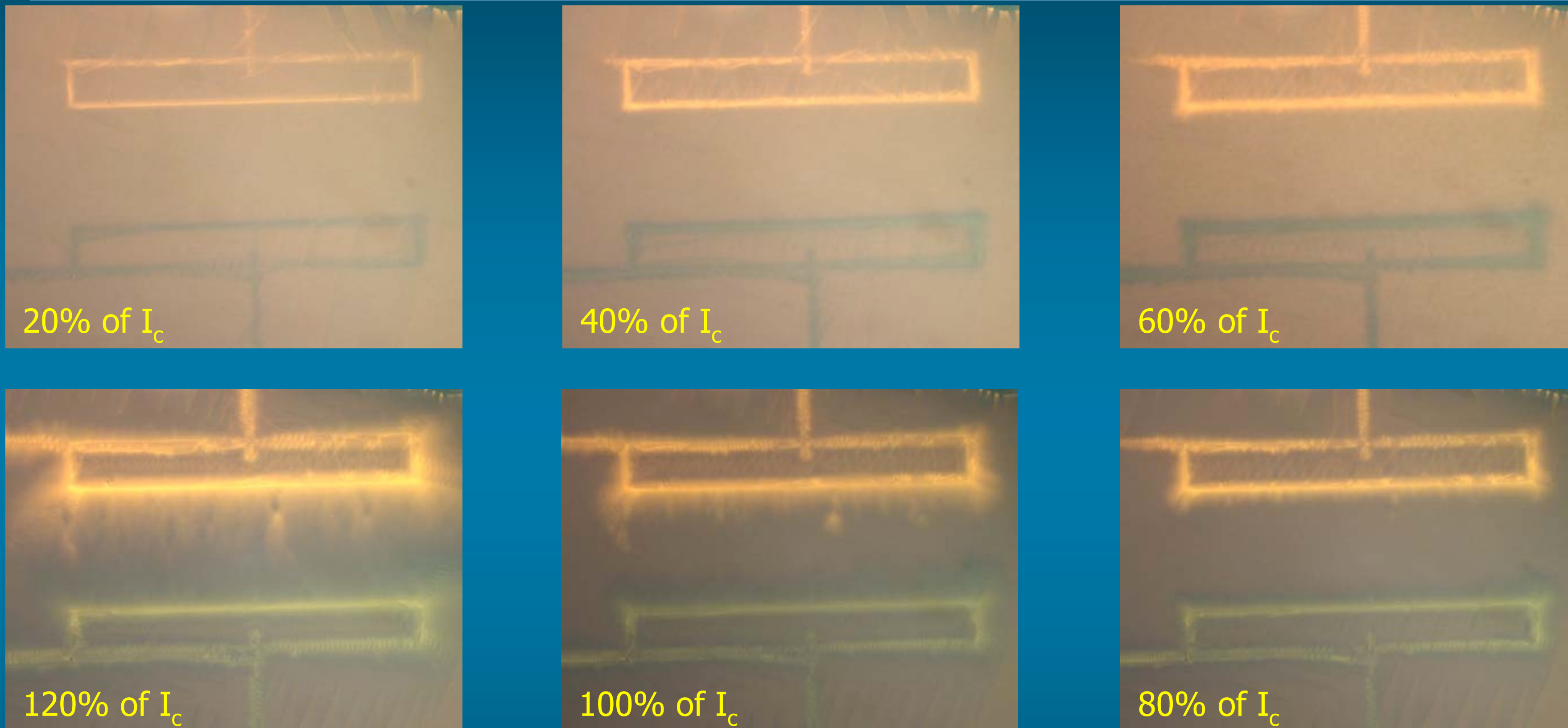


In the middle, however, our coated conductors show excellent properties



- MOI images from M. Feldmann and N. Nelson, Univ. of Wisconsin
  - Link size 300 x 850 µm, thickness = 550 nm, self-field (77 K)
- Taken from middle of a centimeter wide CC

In the middle, however, our coated conductors show excellent properties



- MOI images from M. Feldmann and N. Nelson, Univ. of Wisconsin
  - Link size 300 x 850 µm, thickness = 550 nm, self-field (77 K)
- Extremely uniform flux penetration

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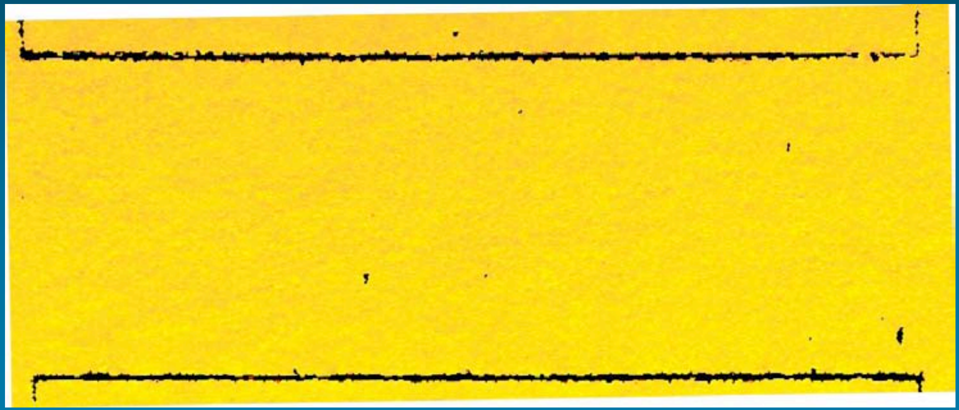
Electron back-scattered diffraction results show very uniform structure

Out-of-plane alignment

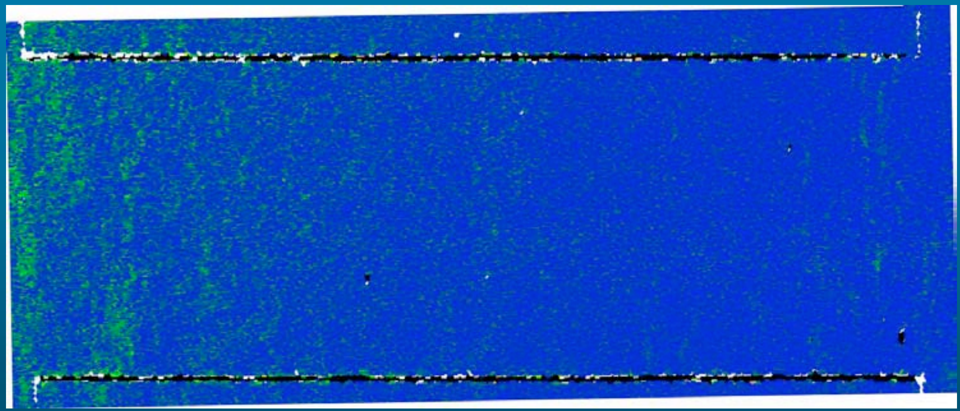


Angle between sample normal and nearest crystal axis

Black = no data (laser cuts)

0° 10°

In-plane alignment



Angle between rolling direction and nearest crystal axis

0° 10°

M. Feldmann and N. Nelson,
Univ. of Wisconsin

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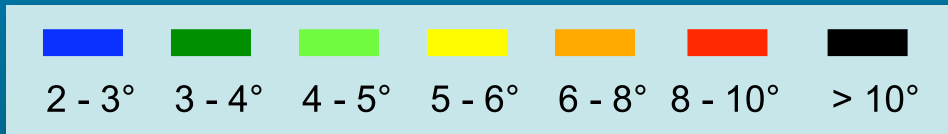
Grain boundary maps also show very uniform structure



Note lack of GB's as compared to other CC's

M. Feldmann and N. Nelson,
Univ. of Wisconsin

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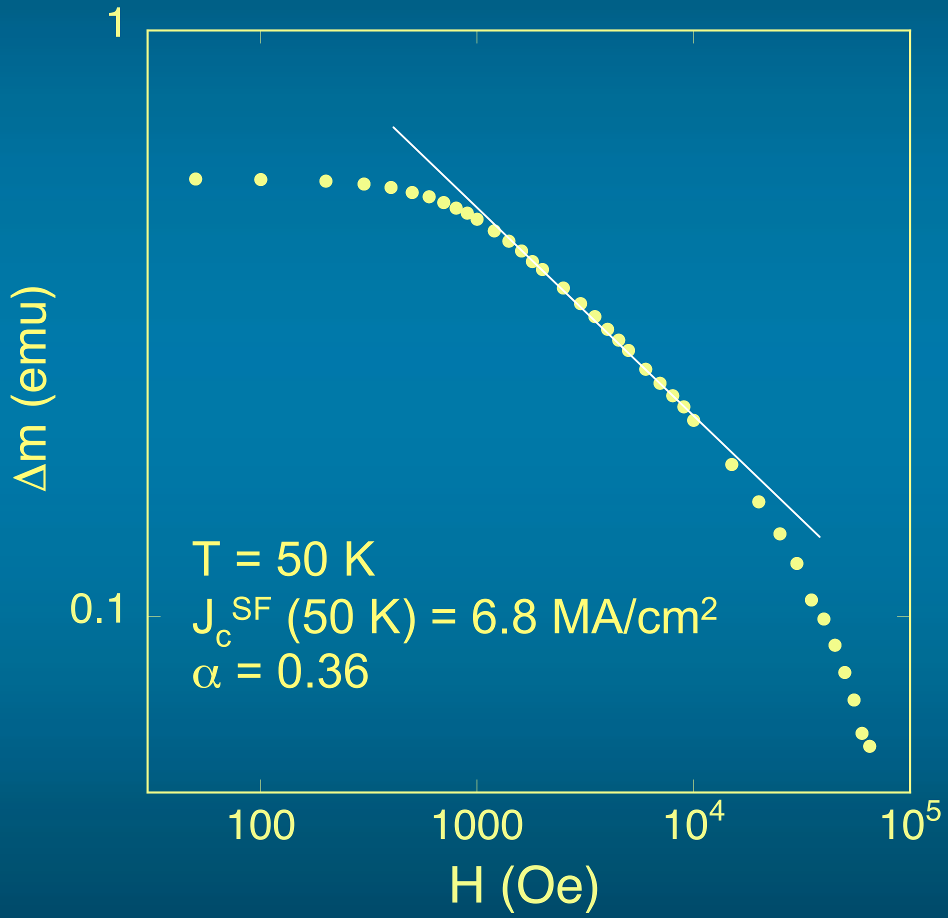
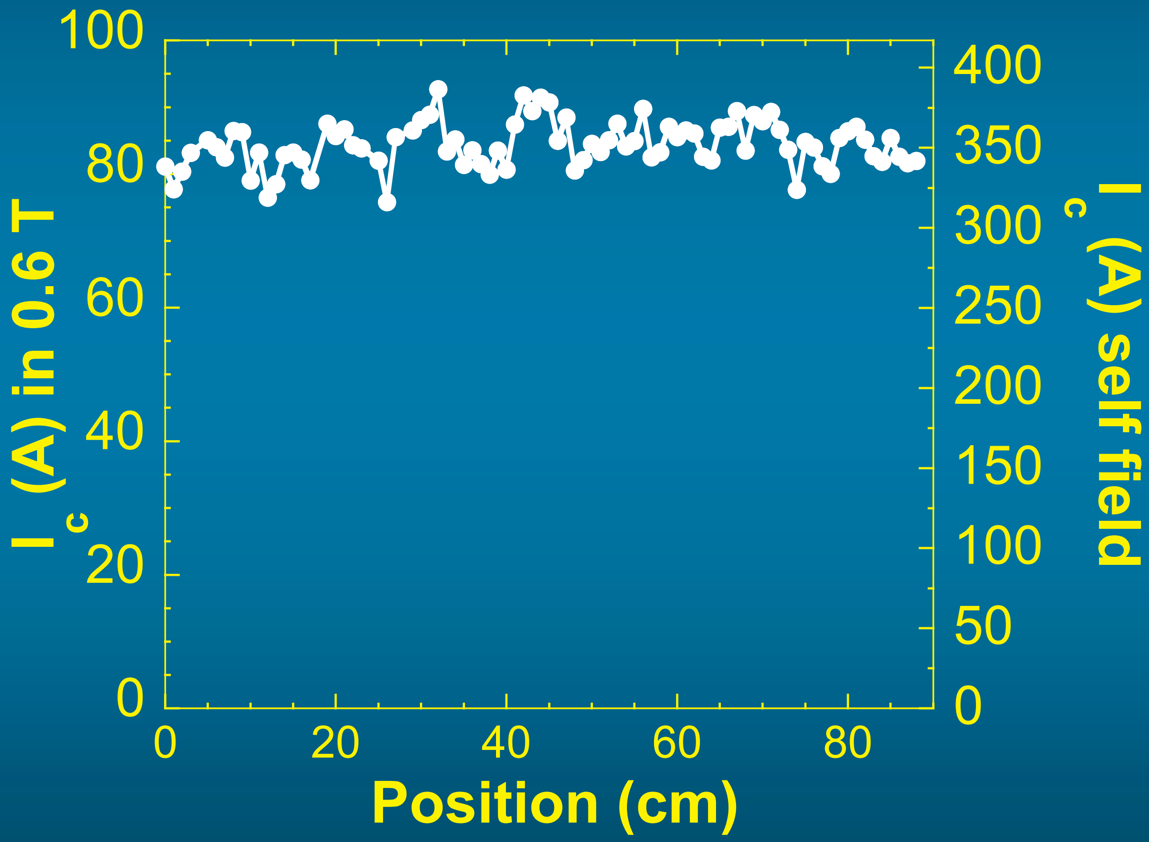
In-field performance of reel-to-reel deposited films

- α is a measure of in-field performance
  - Lower value (0.36) indicates less drop off with increasing field
- The in-field data compare quite favorably to other films
  - 1 μm thick YBCO
  - other YBCO/IBAD-MgO: $\alpha \sim 0.4\text{-}0.5$
  - BZO-YBCO: $\alpha \sim 0.3$

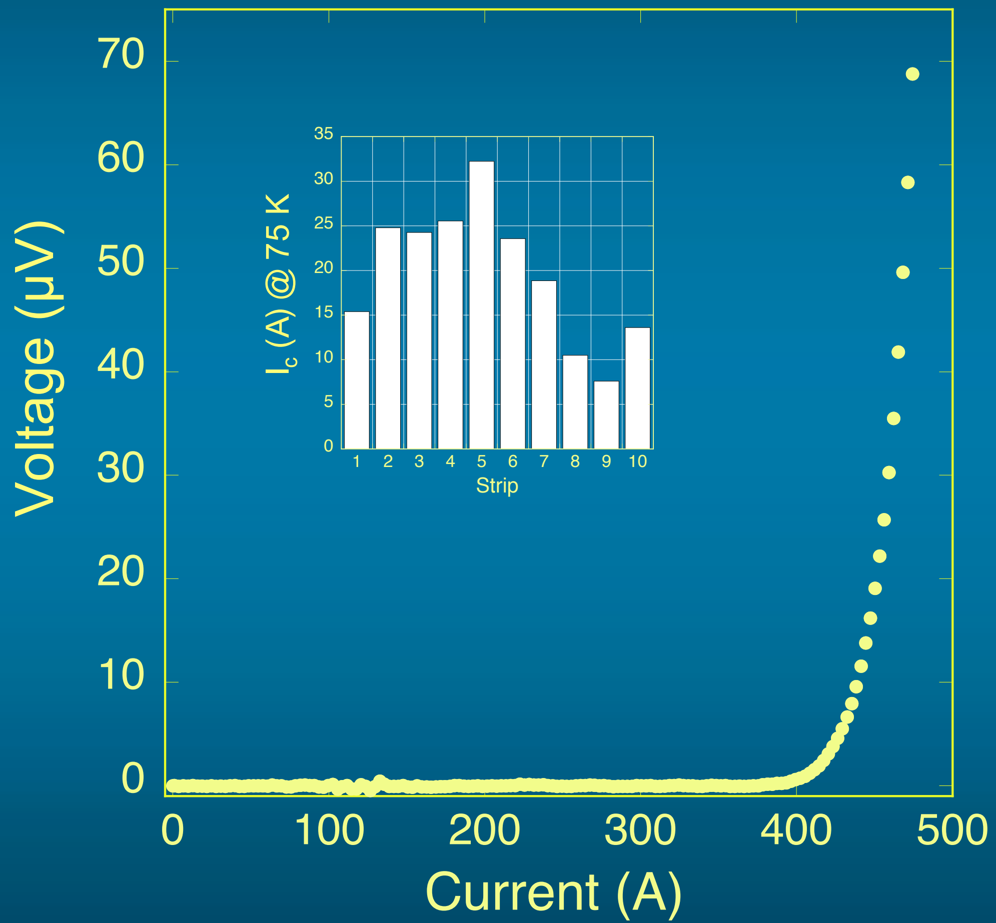


New longer length result of 350 A



- 3 µm thick film - 1.2 m long
- Mean I_c 350 A (75 K)
- J_c = 1.17 MA/cm^2

425 A achieved in a centimeter wide tape



- 4 micron thick YBCO single layer film
- 7 cm long
- I_c = 425 A (75 K)
- N value = 27
- How does slitting to 6 mm affect I_c?

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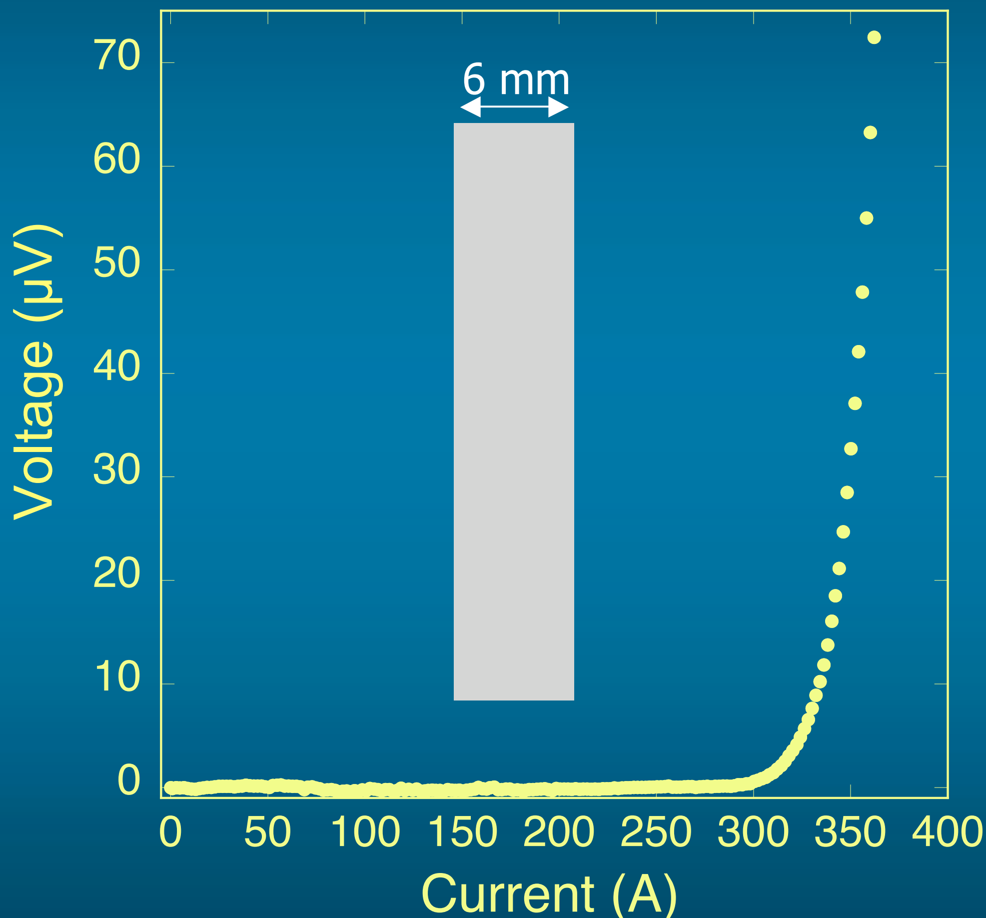
After slitting to 6 mm - 530 A/cm



Take same 425 A tape and slit to 6mm:

I_c = 530 A/cm (75 K)
J_c = 1.33 MA/cm^2

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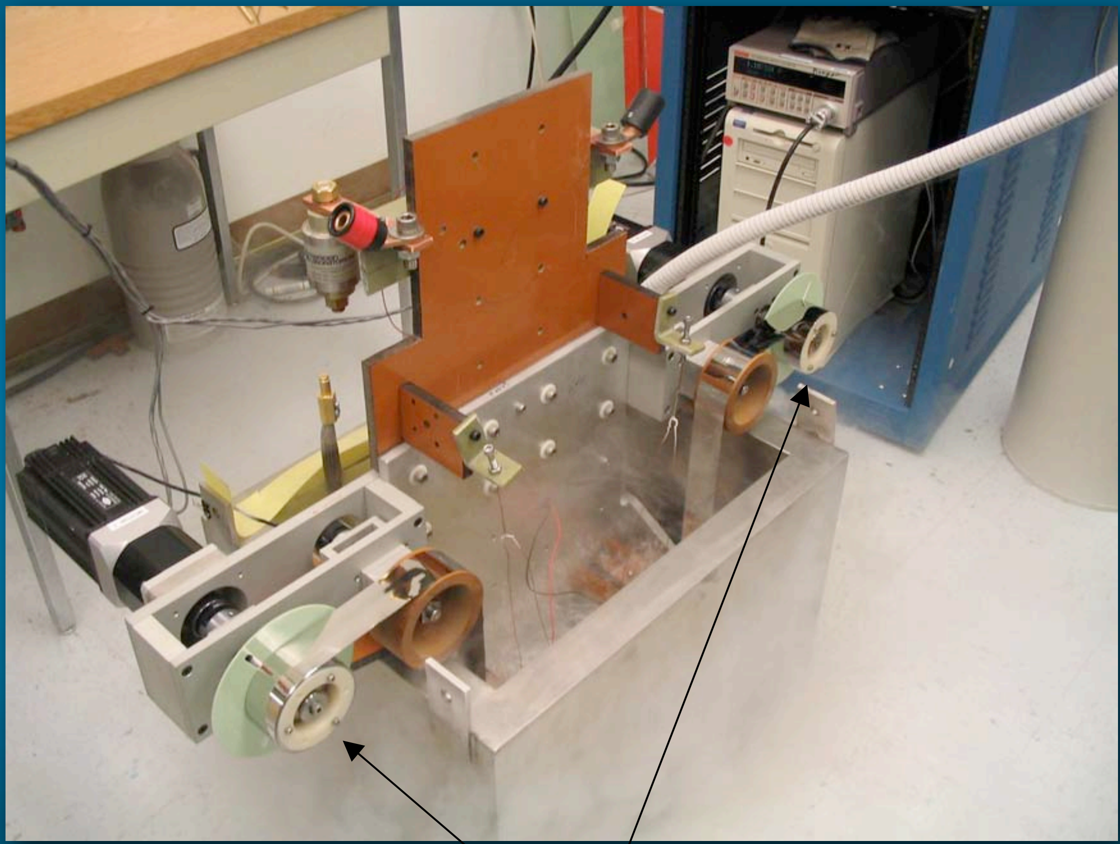
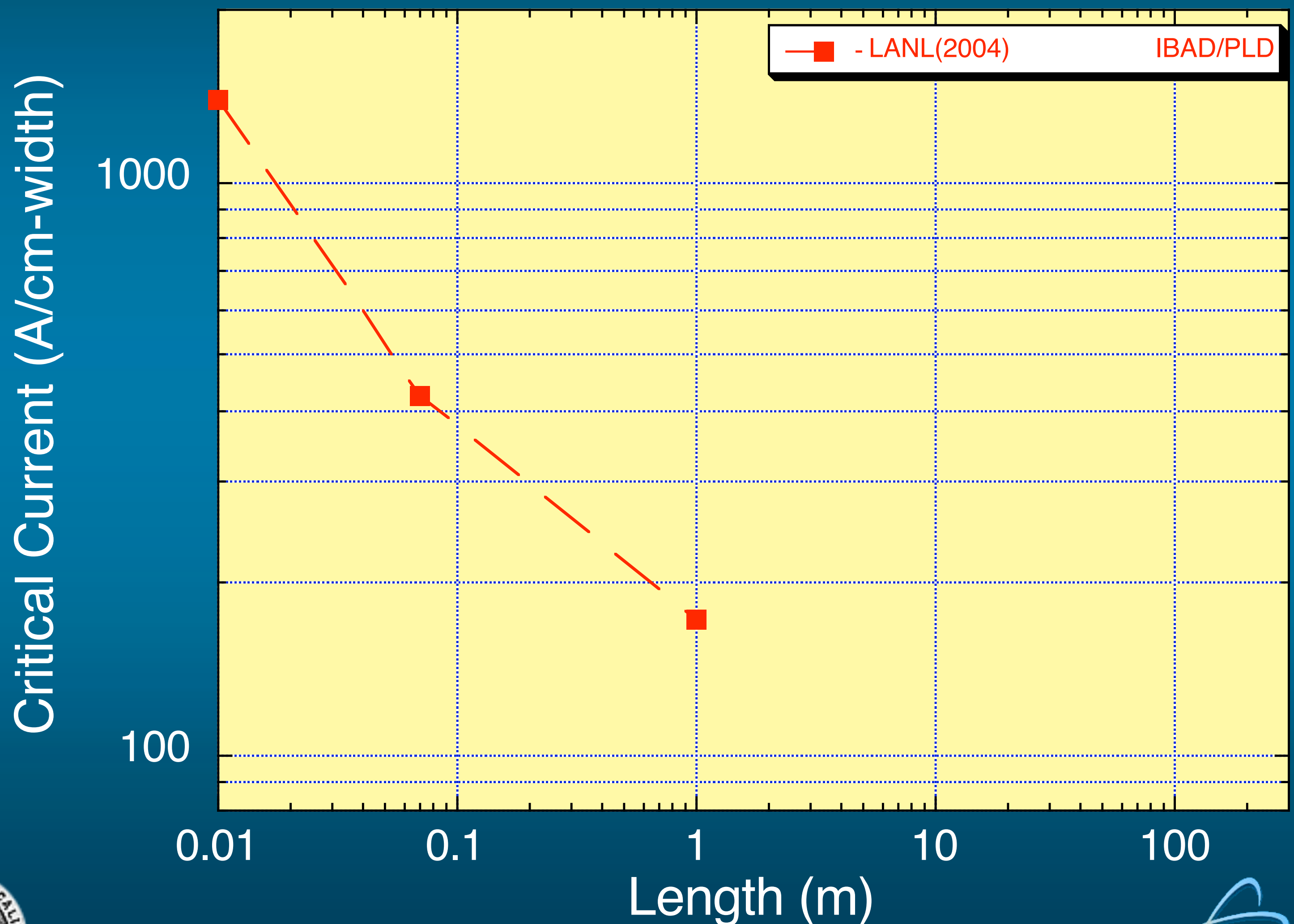
Long and wide tape measurement system

- We added the capability to measure 4 cm wide material
  - In collaboration with our industrial partner

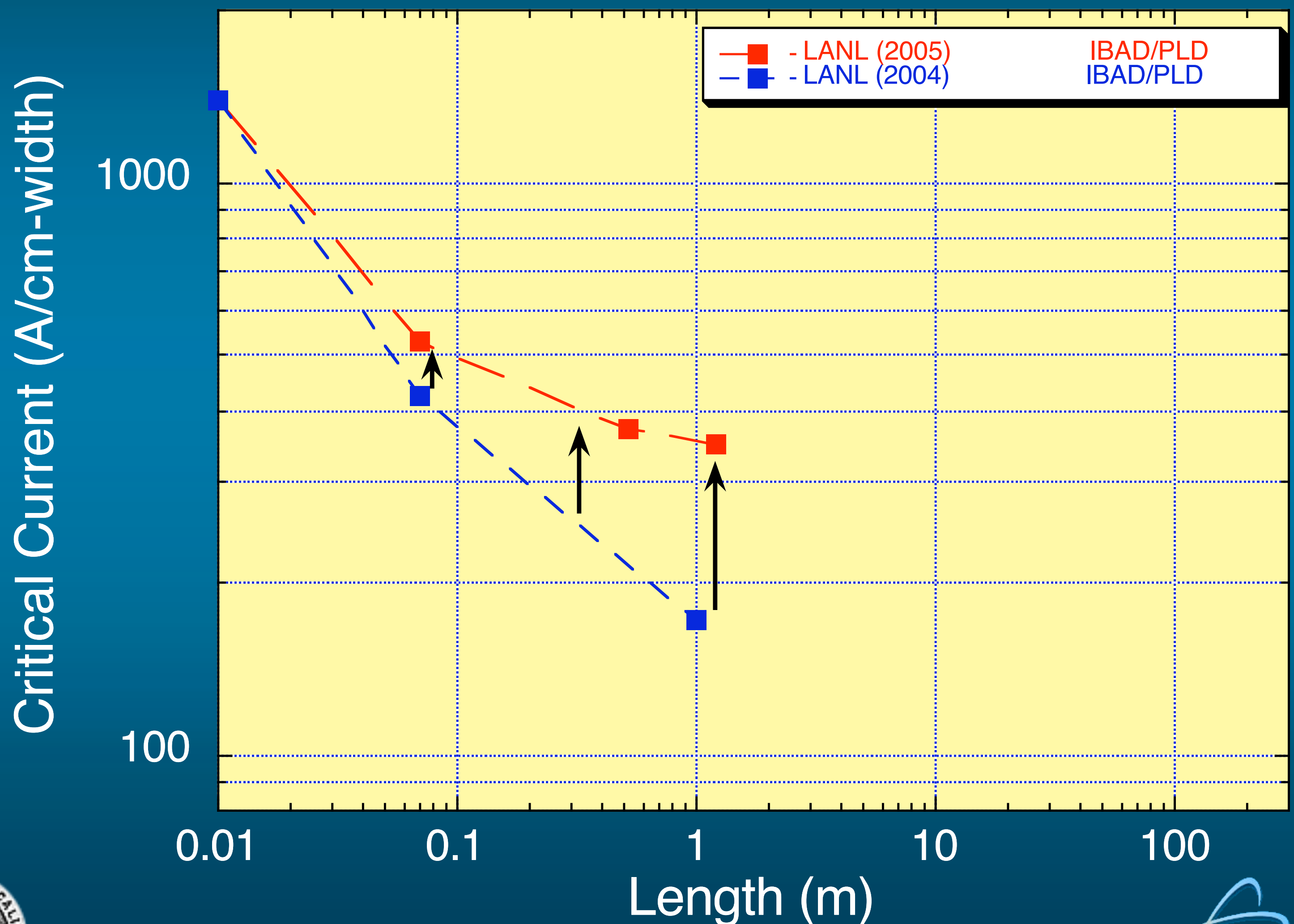


4 cm reels

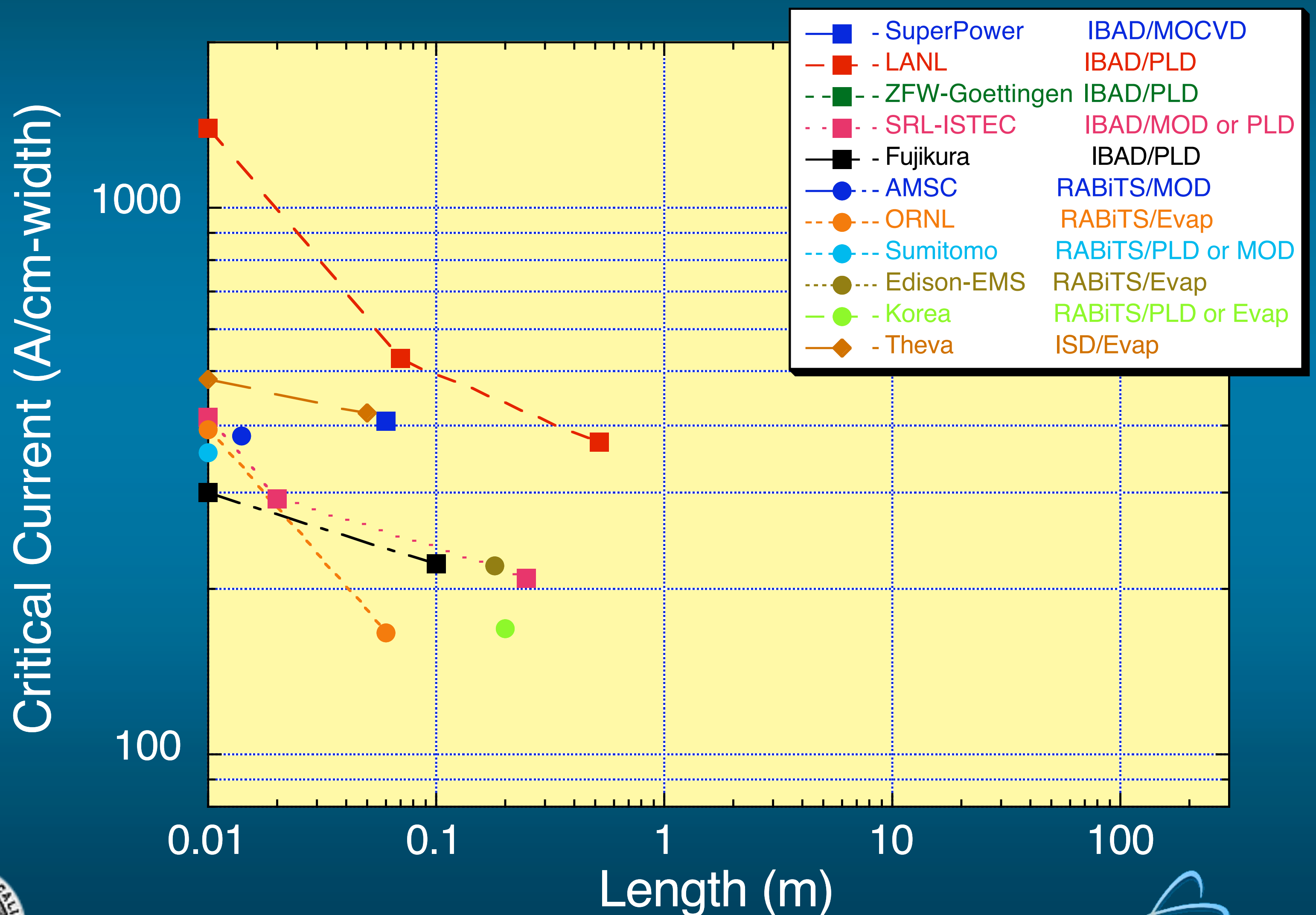
Our results from 2004:



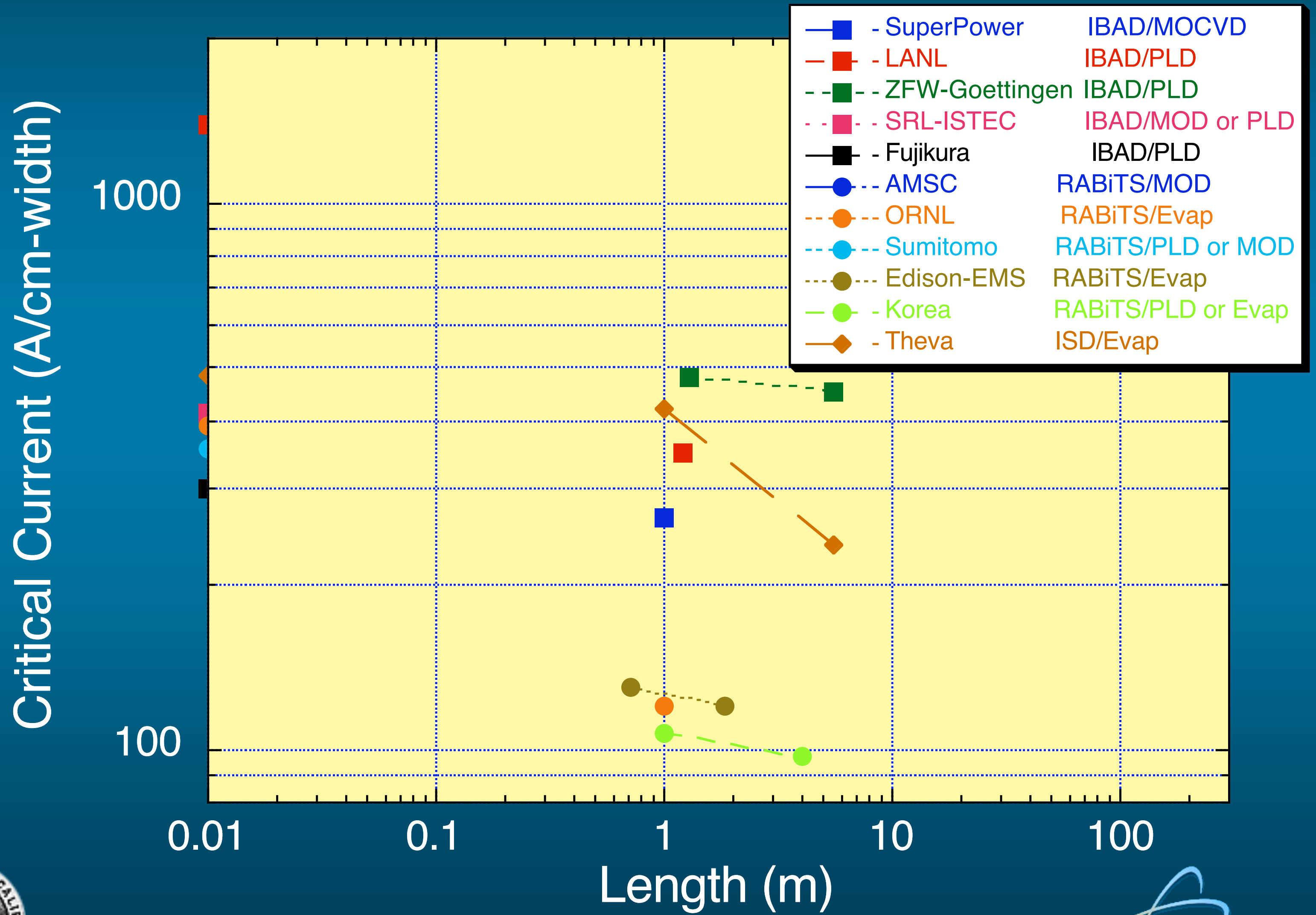
Our recent results:



Worldwide results < 50 cm



Worldwide results: 50 cm - 6 m



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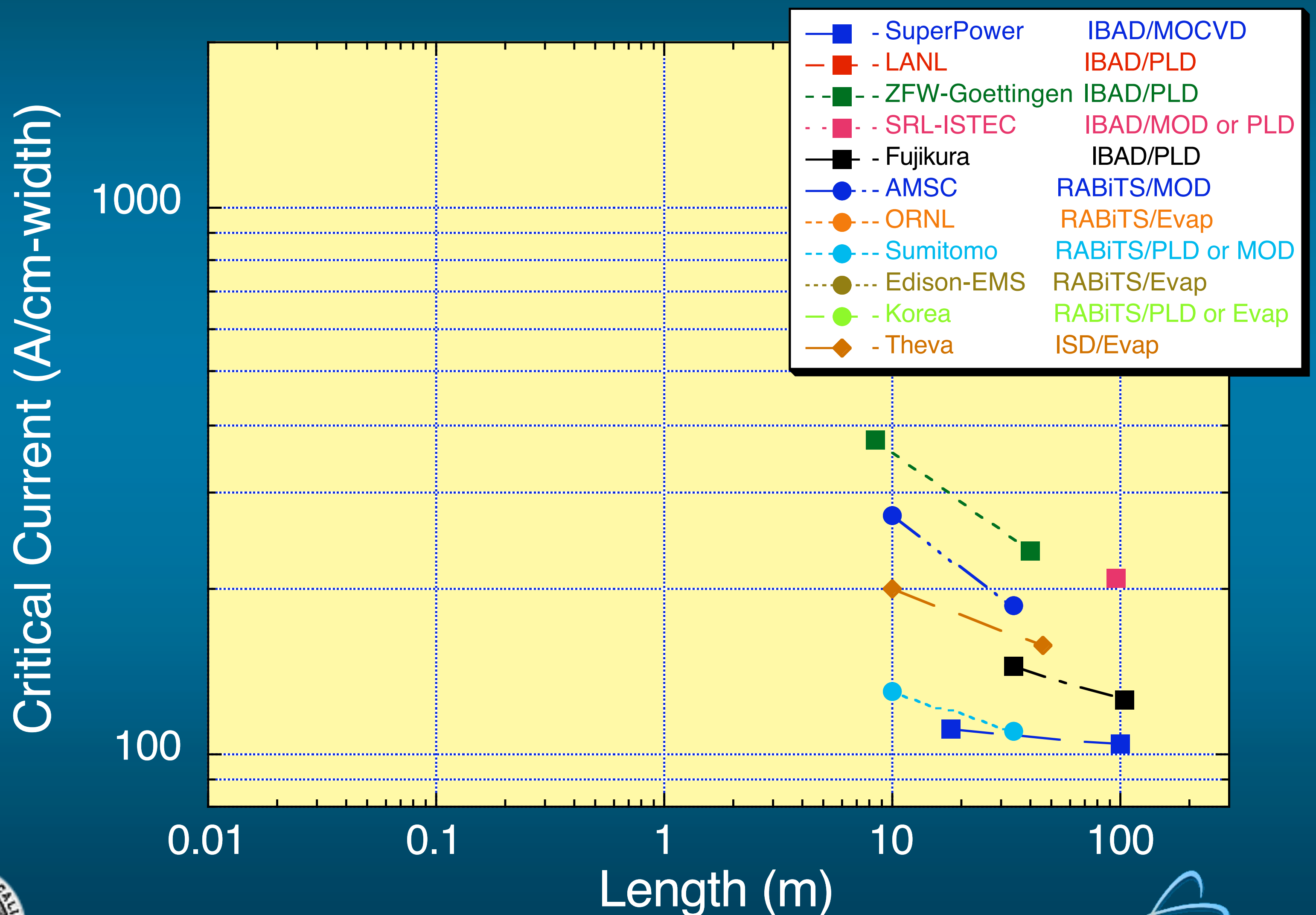
Worldwide results: > 6 m



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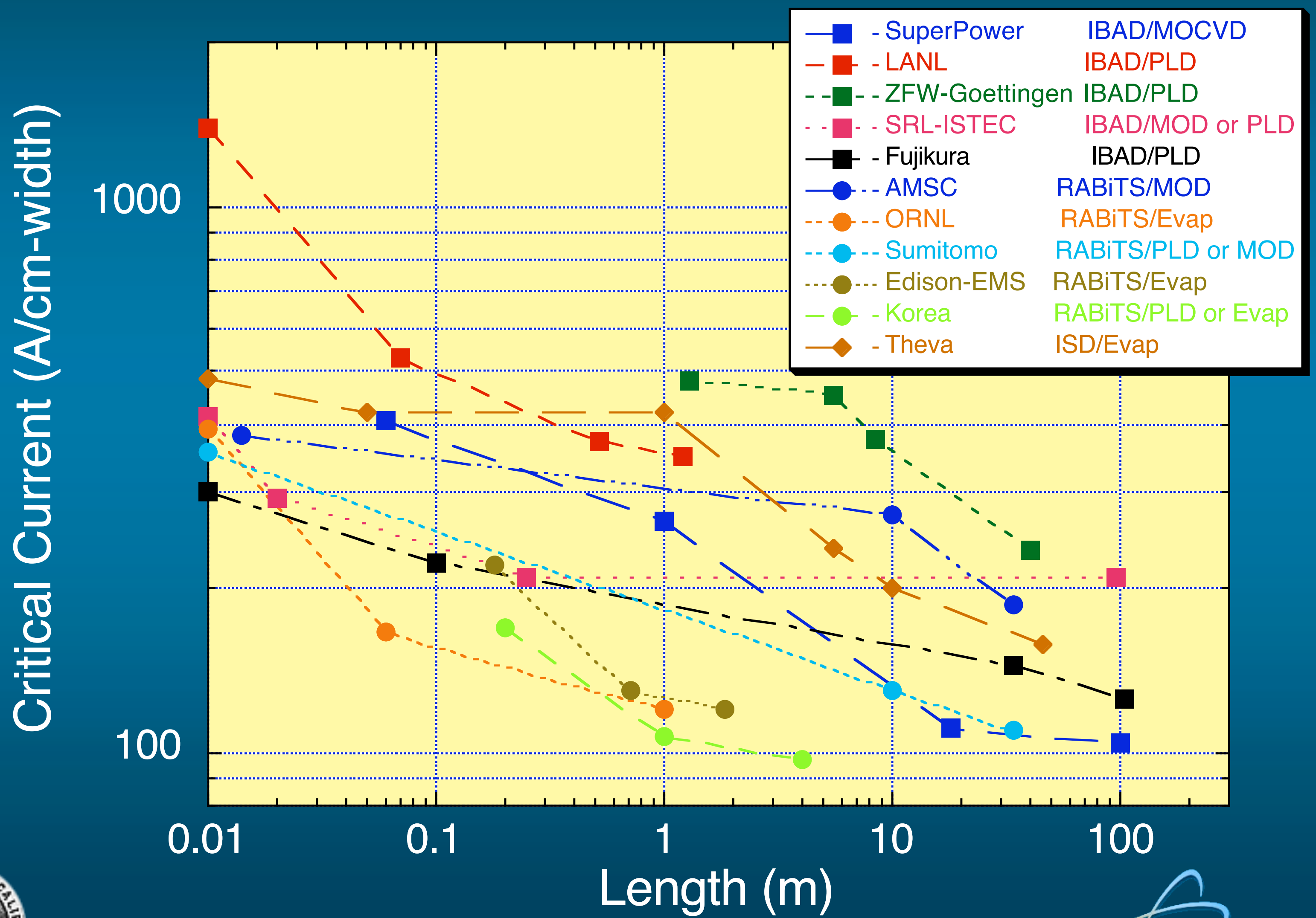
Worldwide results:



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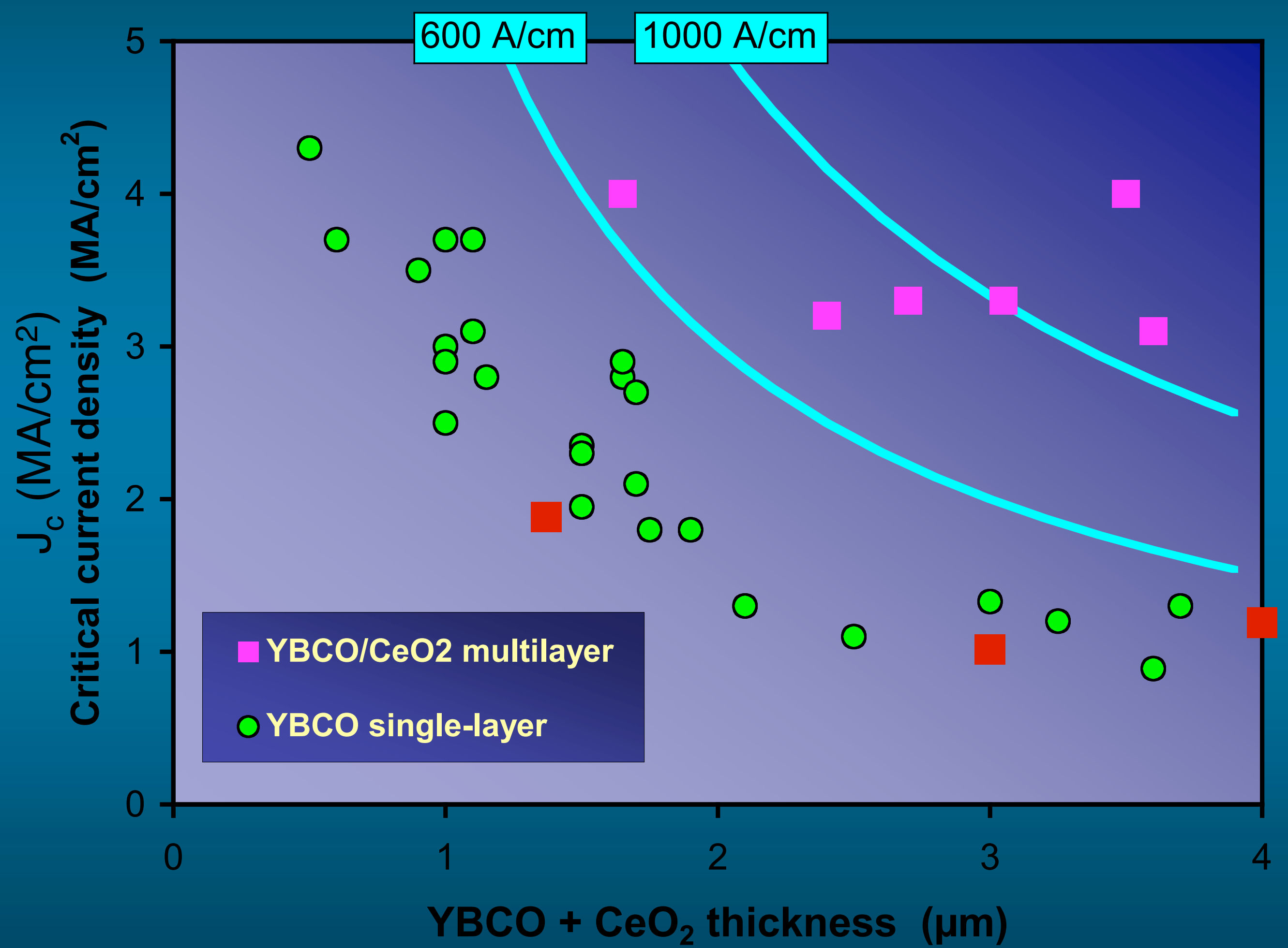
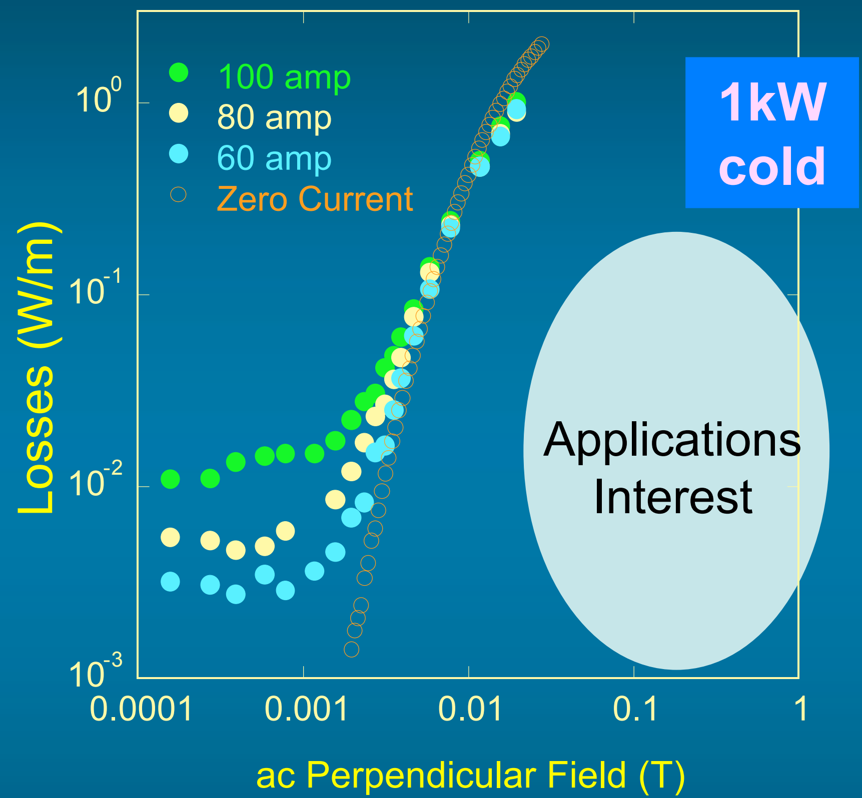
The single layer reel-to-reel deposited films are now reproducibly achieving values from microbridge results



S.Foltyn, 2004 Annual Review

AC Losses are an important problem

- Changing field and/or current dissipates energy in coated conductors
- Need to remove this energy (heat) by refrigeration
  - Economic problem
  - Engineering problem
- Losses are significantly higher than we would like
- In particular
  - Losses due to ac fields perpendicular to tape face
- Need to 'develop' the conductor
  - Simply increasing Ic will not do it



eg Coil: 10km of tape
10% in perpendicular field of
10mT

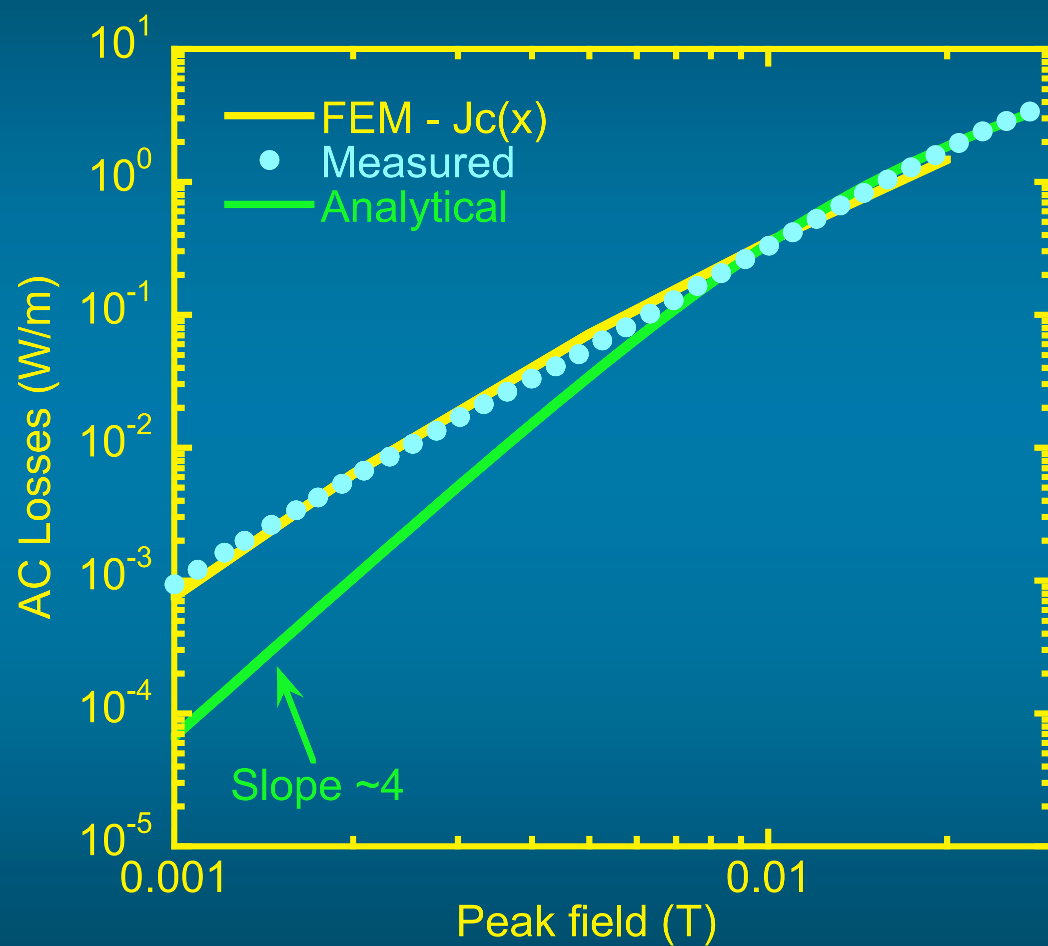
Los Alamos

There *are* techniques for reducing AC losses in practical applications

- Combination of
  - Experiment
  - Numerical models
  - Highly integrated with CC production effort
- Unique to LANL
- Reduce losses at both the conductor and the coil level
- Report here work on low ac loss conductors
  - Low loss 2D Conductor design
  - Manufacture route
  - Future paths

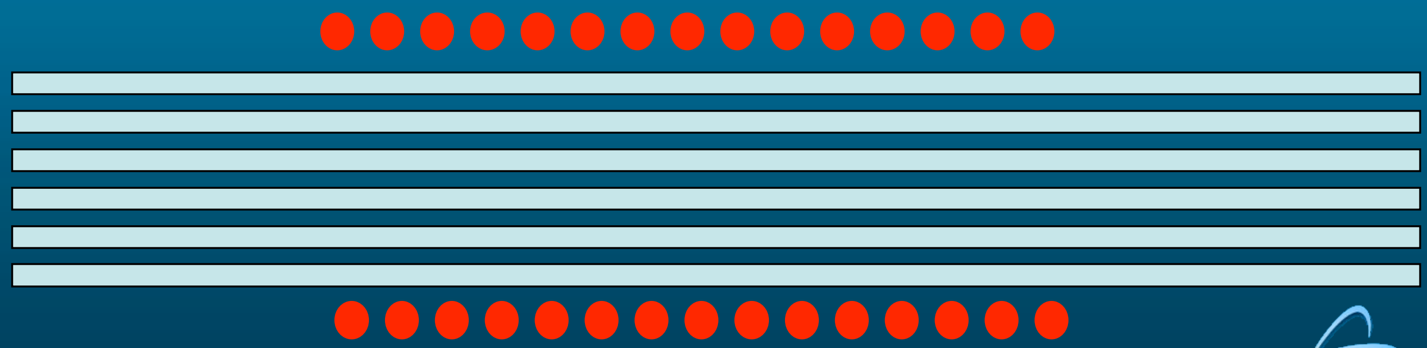
Magnetic losses of individual tapes - characteristics

- Analytic theory and FEM (constant J_c)
  - **loss~field⁴** for fields below penetration
- Experimental results on varied samples
  - lower slope, typically 3-3.6
- Hypothesis
  - non-uniform J_c across tape
- Test
  - FEM with $J_c(x)$ good agreement with experiments



How can we reduce the magnetic losses of individual tapes?

- Losses inversely proportional to the square of the width
- Implies multifilamentary tapes for low losses
- The filaments must experience the same electromagnetic environment
  - Magnetic flux must be able to get between all filaments



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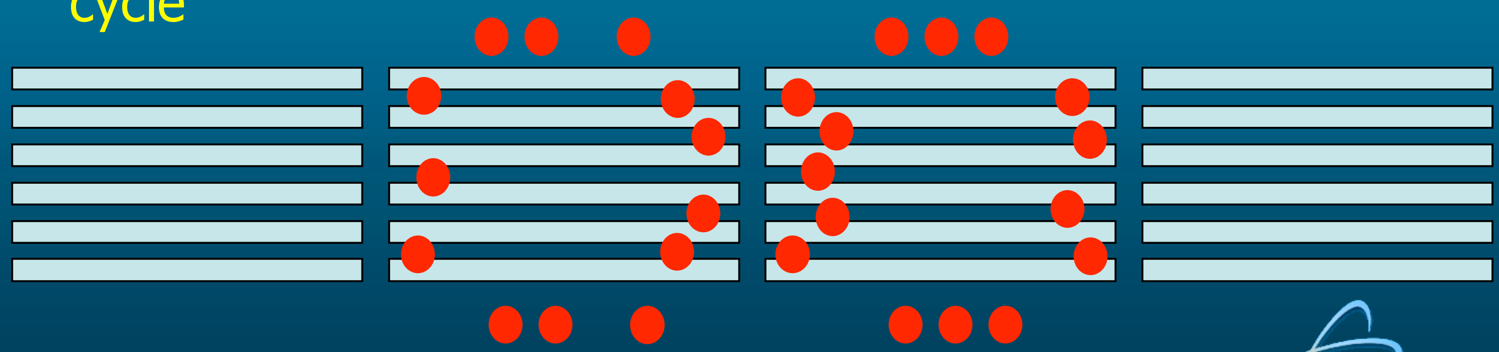
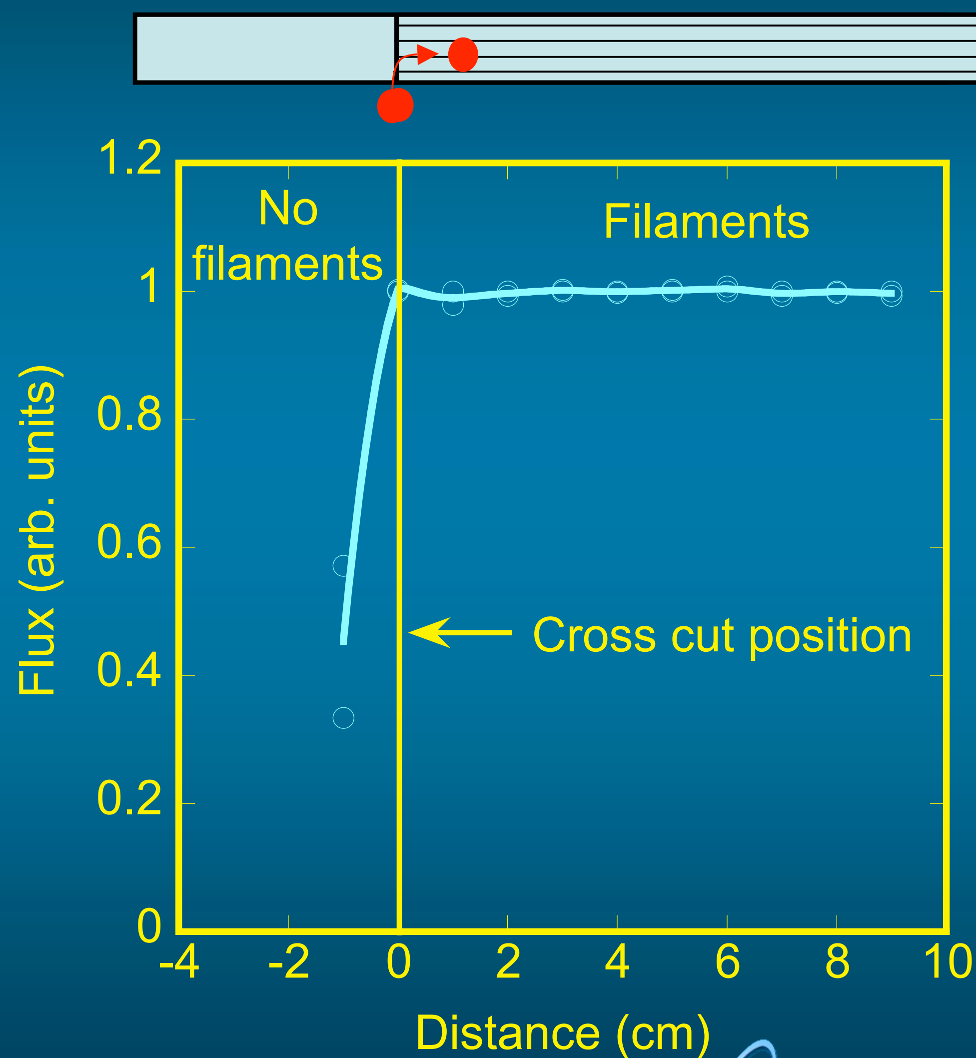
How can we reduce the magnetic losses of individual tapes?

- Losses inversely proportional to the square of the width
- Implies multifilamentary tapes for low losses
- The filaments must experience the same electromagnetic environment
  - Magnetic flux must be able to get between all filaments
  - Transposition…not easy in practice!
- Alternative way
  - striate the superconductor into filaments AND periodically break the filaments with transversal cross-cuts
- Magnetic flux can enter between the filaments during each ac cycle



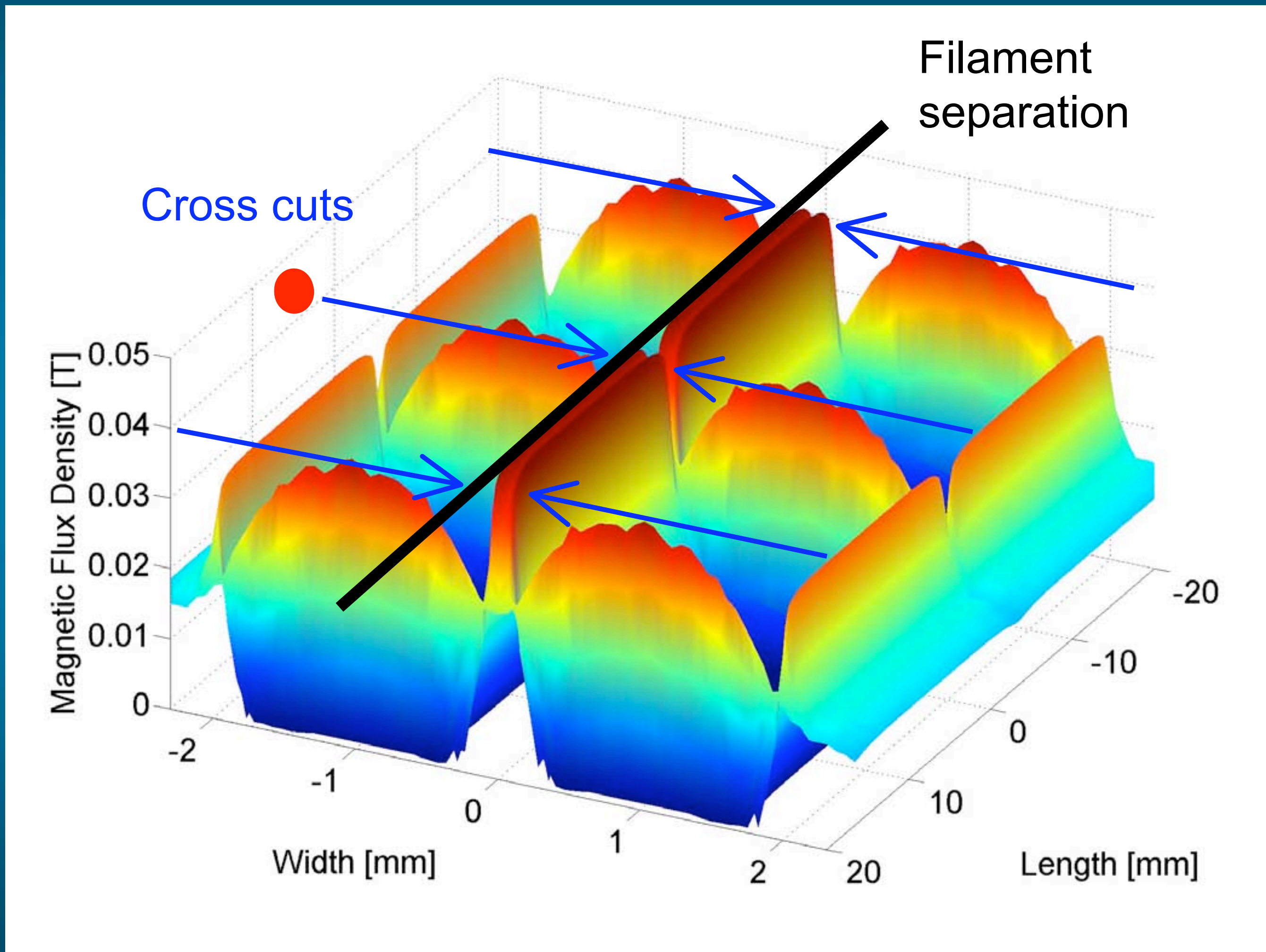
How far can the flux enter from a cross-cut?

- Experiment
  - 100 Hz perpendicular AC field
  - Flux can only enter at the cross-cut
  - Measure flux between filaments
  - Function of distance from entry point
- On the left of the cross-cut no flux in the sample
- In the filament region
  - Flux moves at least 10 cm in a cycle
- Only 5 cuts/m necessary for loss reduction at 60 Hz



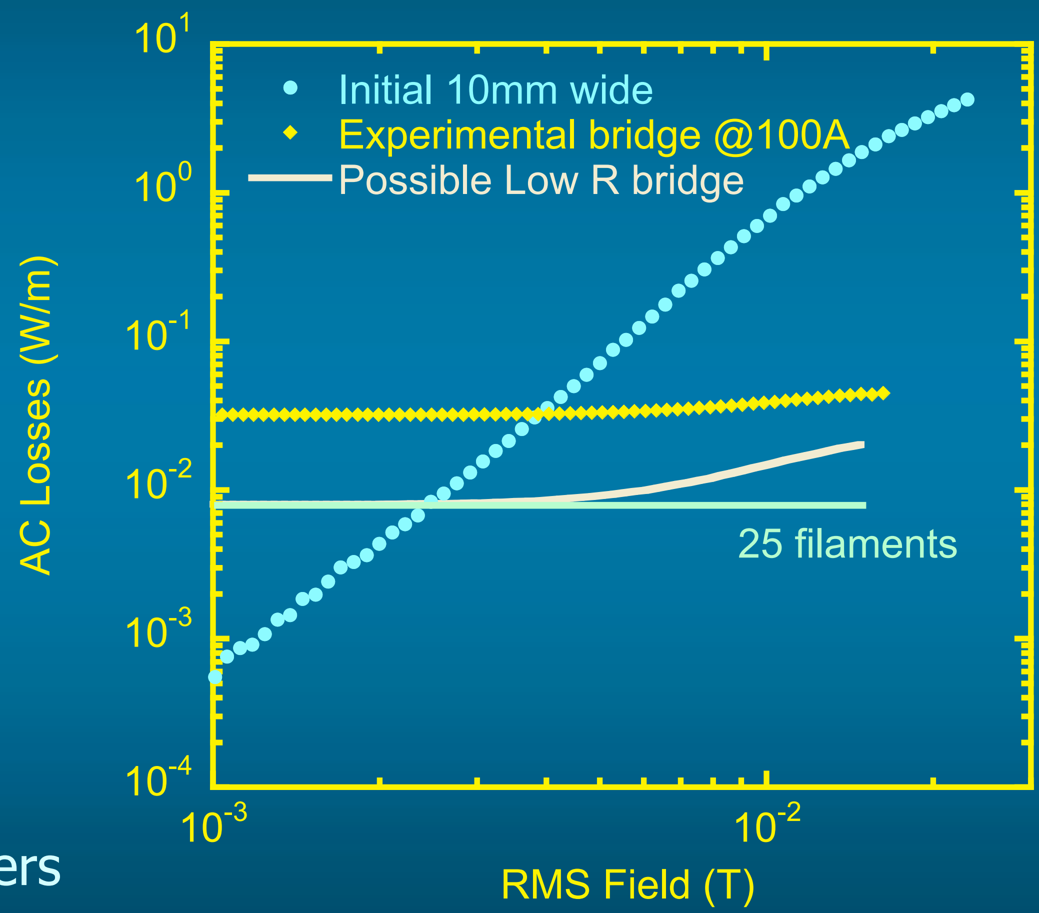
Los Alamos

FEM analysis confirms the effect



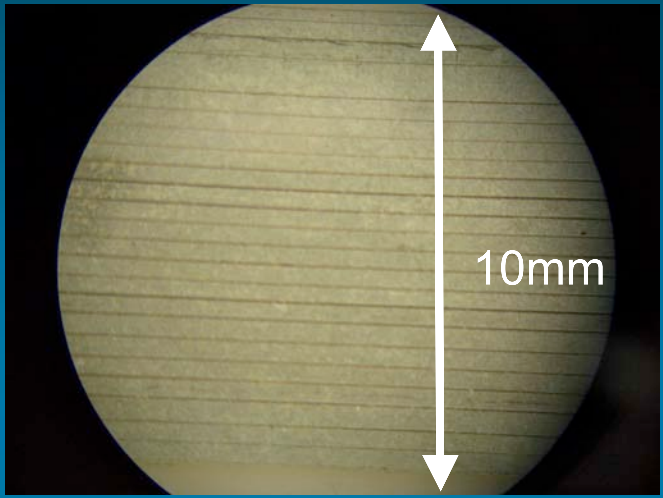
Losses are reduced by nearly two orders

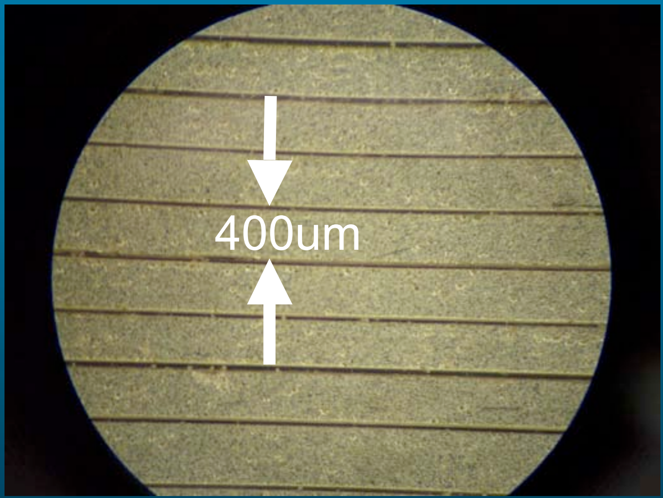
- Magnetic losses tape 10mm
- 10 filaments + 5 cross-cuts/m
  - Nearly 2 orders of magnitude reduction
- Transport current: RI^2 contribution of the bridge
- Low R bridge + 25 filaments
  - Losses potentially reduced by nearly 3 orders



Low cost route to filament manufacture

- Introduced a technique for cutting long samples into several filaments in a short time
  - Continuous process
  - Low additional cost
  - 25 filaments, 10 mm wide
  - Speed ~ 1 meter/min
- We have made lengths to 50 cm





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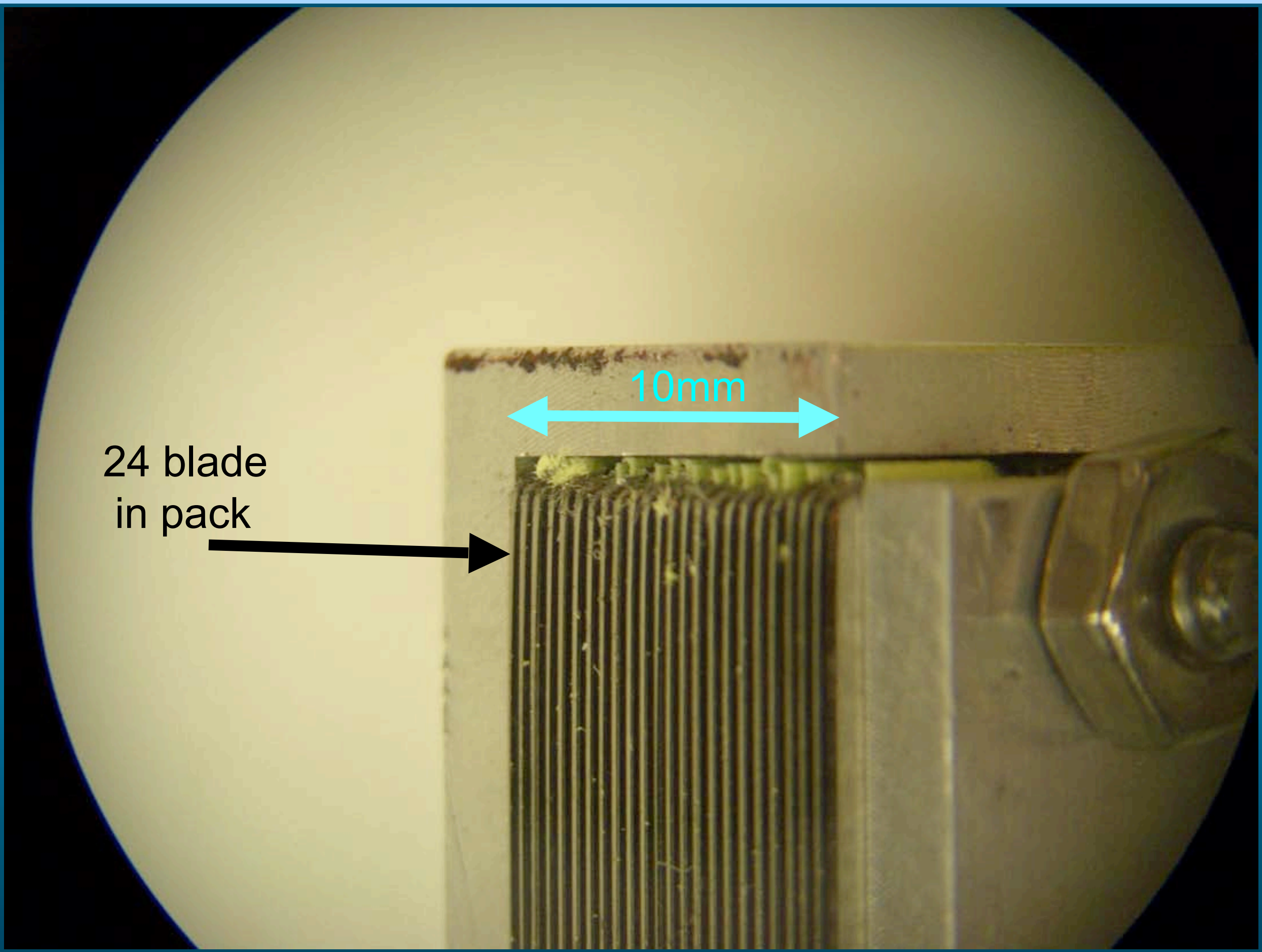
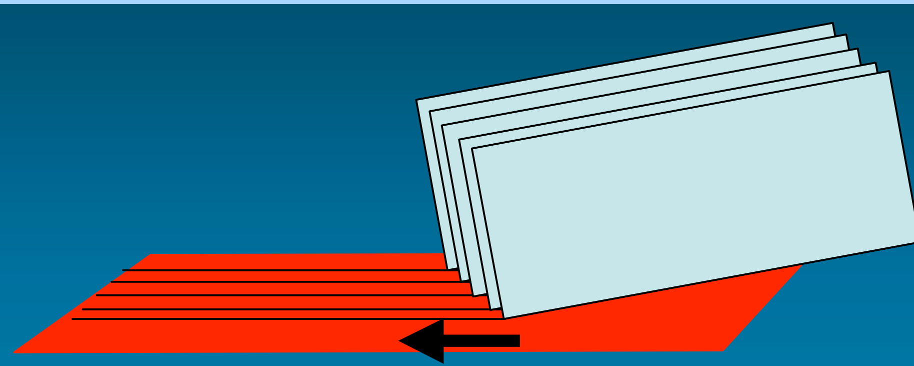
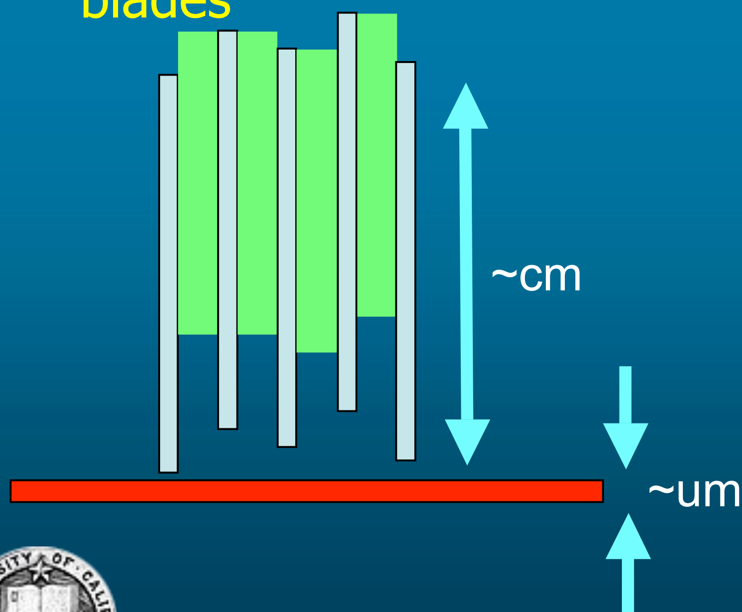
Filaments cut by steel blades held in pack

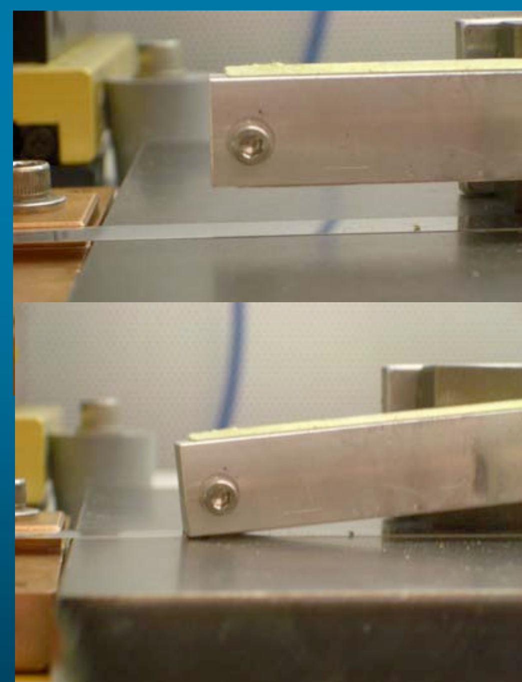


Cut filament using a simple blade stack

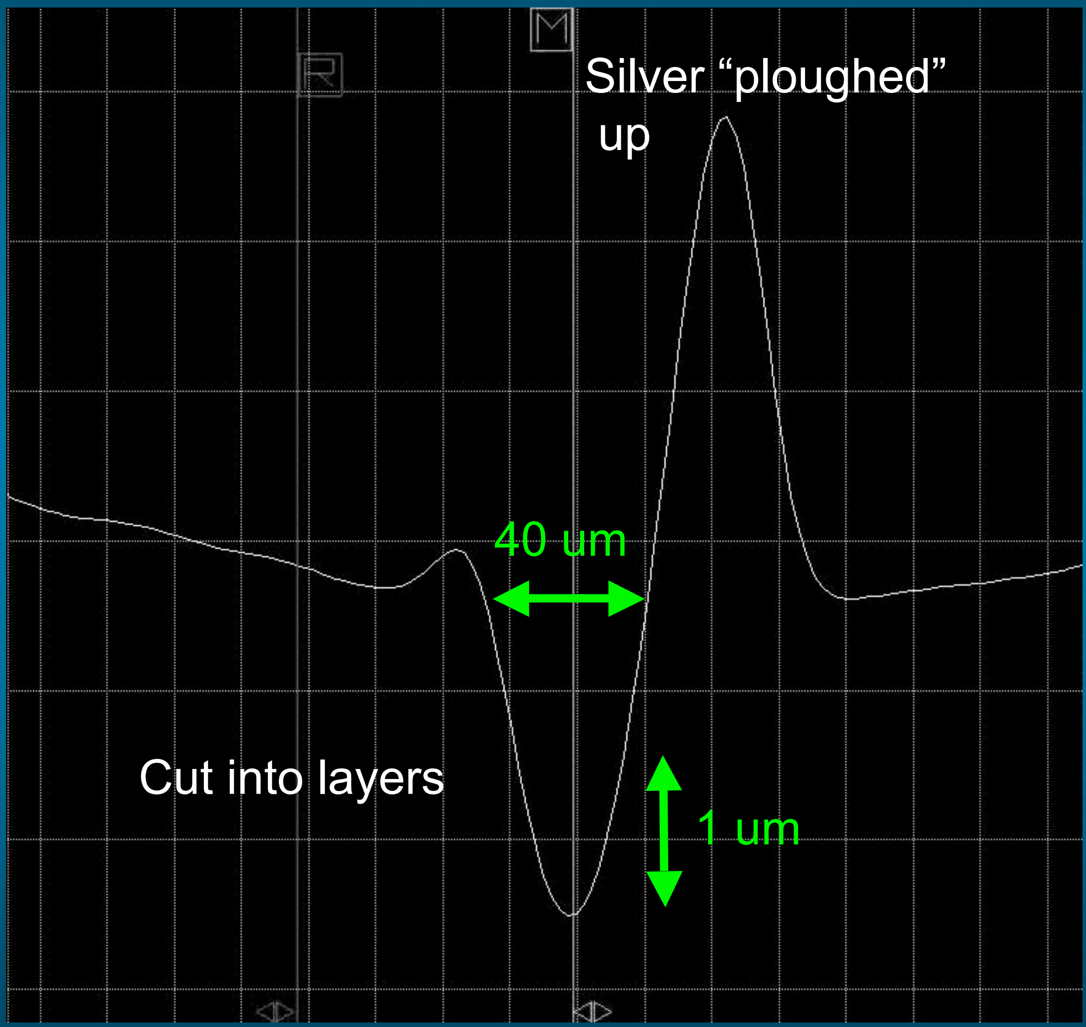
- Standard microtome blades
- Move tape past blade pack
- Difficult to align blades to µm
- Ensure alignment by allowing flexure between blades



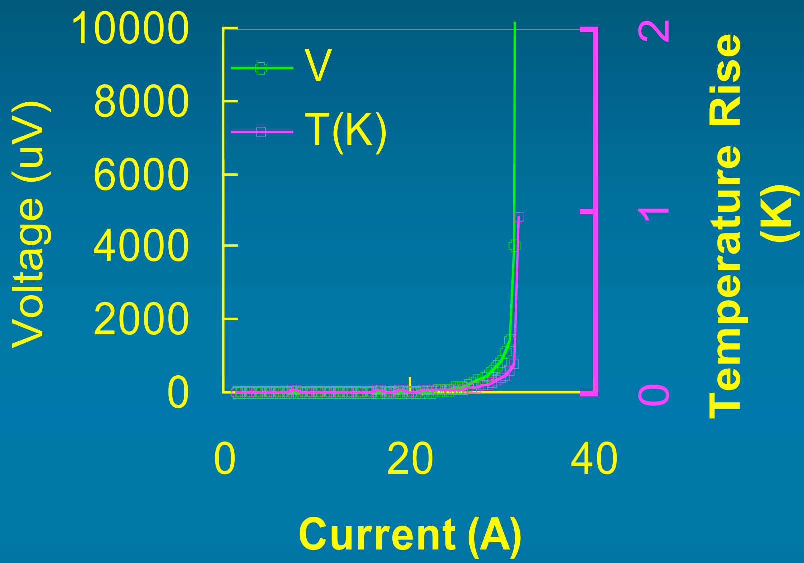




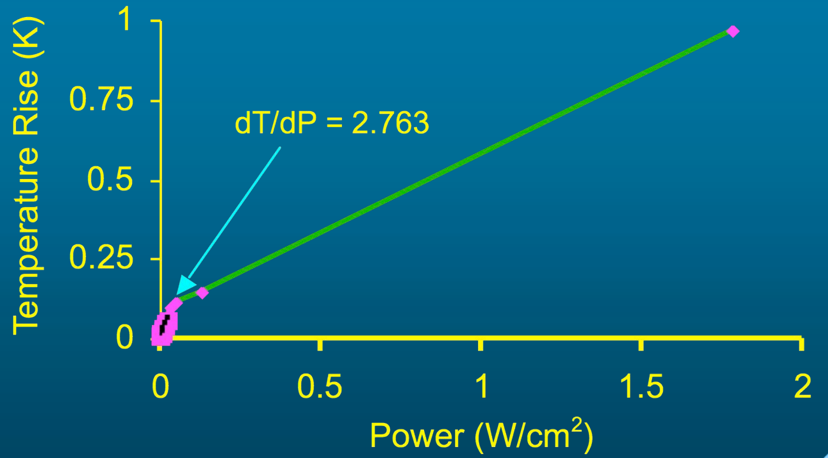
Profile scan shows filament gaps



Stabilization: As I_c's increase coated conductors need more over current protection than few µm Ag provides



Thermal run-away at $1.1*I_c$



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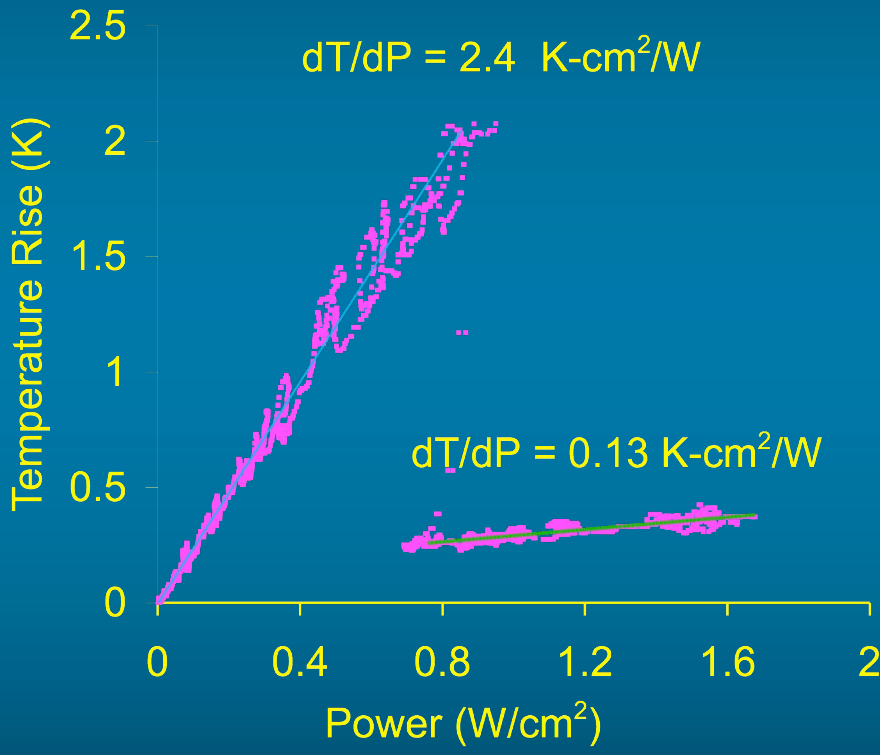
Copper plating on one side stabilizes and allows boiling transition

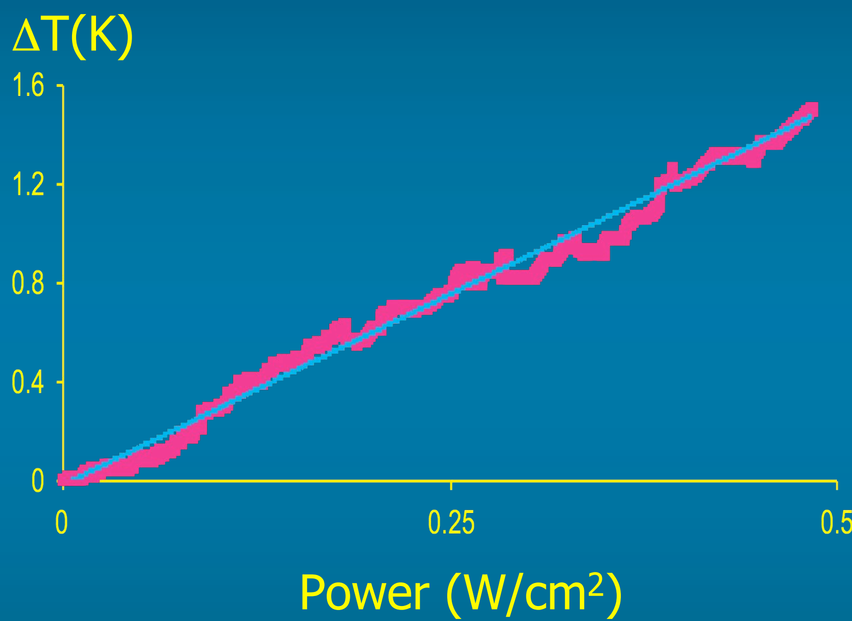
- YBCO CC w/ 50 μm single sided Cu
- No damage to nearly 3 x I_c
- Temperature increases enough to initiate boiling
- dT/dP convective = 2.4 Kcm^2/W
- dT/dP boiling = 0.13 Kcm^2/W



Los Alamos

No boiling transition in double sided plating

- YBCO CC w/ 50 μm double sided Cu
- Repeated excursions to 3xI_c show no change in V-I curve
- Max power ~0.5W/cm^2
- Temperature doesn't increase enough to initiate boiling
- dT/ dP = 3.1 K-cm^2/W
- Heat Transfer Coefficient ~0.3 W/cm^2-K



Performance - 2005 Research Park Goals for CC Fabrication & Characterization

- **Goal:** Develop robust CC IBAD architecture needed for the different YBCO processes by working with industry ✔
  - Simplified architecture: removed a-Al_2O_3 layer
  - Increased the thickness of MgO layer
  - More robust
  - Better texture
- **Goal:** Add dc sputtering capability to IBAD processing system; utilize for diffusion barrier ✔
  - System is installed and operational
  - New barrier materials explored

Performance - 2005 Research Park Goals for CC Fabrication & Characterization

- **Goal:** Reduce I_c variation to < 2% on a 2-cm measurement length scale over > 1 m: understand the cause of variations
  - Reduced to 7%
  - Discovered positional variation across tape
  - Focused on I_c drop outs as opposed to spread
- **Goal:** Fabricate CC with I_c > 500 A @ 75 K (5 m, J_c > 1 MA/cm^2)
  - Dropped "5 m" length as a goal this year; too resource intensive
  - 350 A on a 1 cm wide tape (J_c > 1 MA/cm^2), 1.2 m
  - 530 A/cm on reduced width (6 mm), 7 cm
  - All samples deposited on moving tape
  - All J_c > 1 MA/cm^2

Performance - 2005 Goals for CC Fabrication & Characterization

- **Goal:** Reduce ac losses in the CC wire by one order of magnitude; examine transition from 2D to 3D geometry
- Goal (from ac loss presentation last year):

1. *Not to present this talk to you next year!*
   - *Present it in "wire session"* ✔
   - *AC loss reduction a central part of coated conductor development* ✔
2. *Develop and test conductor architecture*
   - *Capable of carrying 100 A/cm width ac current in 100mT ac field without quenching (present limit is 10 mT)* **Copper plating** ✔
3. *Develop and test a conductor production technique (lengths > 10cm)*
   - *Capable of carrying 100A/cm width ac current in greater than 10mT ac field without quenching.* **Copper plating** ✔
   - *Capable of carrying 100A/cm width ac current in 10 mT ac field with ac losses **ONE** order of magnitude below present values* ✔

Length >30 cm, losses 5% in 30 mT field

Los Alamos

Results - 2005

- High rate IBAD-MgO at 270 m/hour with 7° in-plane texture
- ac loss reduction by two orders of magnitude
- 530 A/cm-width on 7 cm of moving tape
- 350 A on 1.2 m long, 1 cm wide tape
- Fast, low-cost process for producing filaments
- IBAD-TiN with 7° in-plane texture - potential for conducting buffer stack

Research Integration - 2005

- Polished long lengths (>100 m) of tape for AMSC and SuperPower; special processes for their needs
- Provided IBAD tape to industrial and university partners
- Transferred reel-to-reel ac loss measurements to SuperPower
- Developed equipment, characterized numerous samples from collaborators
  - 4-cm wide I_c measurement
- Collaborated with Sandia on barrier/nucleation layer by sol-gel
- Ongoing programs with Stanford, University of Wisconsin
- New CRADA with MetOx being finalized

Goals for FY 2006 - LANL CC Development

- Fabricate a 1 kA CC (@ 75 K) by continuous processing
- Reduce ac losses of CC in fields > 0.1 T
- Increase the speed of the rate limiting step in template fabrication by one order of magnitude
- Work with industry to produce longer length, lower ac loss conductor
- Examine further barrier/smoothing layer with sol-gel of a-Y_2O_3 and compare with e-polishing
- Develop fabrication processes for coating conductors in a 3D geometry

Summary

- IBAD producing up to 10 m lengths of template tape (~ 4 - 6° FWHM in-plane)
- IBAD demonstrated at 270 meters/hour
- PLD producing CC meters, thick layers possible, high currents demonstrated
- ac loss reduction by two orders of magnitude